RANS Modeling of Benchmark Shockwave / Boundary Layer Interaction Experiments

Abstract: This presentation summarizes the computations of a set of shock wave / turbulent boundary layer interaction (SWTBLI) test cases using the Wind-US code, as part of the 2010 American Institute of Aeronautics and Astronautics (AIAA) shock / boundary layer interaction workshop. The experiments involve supersonic flows in wind tunnels with a shock generator that directs an oblique shock wave toward the boundary layer along one of the walls of the wind tunnel. The Wind-US calculations utilized structured grid computations performed in Reynolds-averaged Navier-Stokes mode. Three turbulence models were investigated: the Spalart-Allmaras one-equation model, the Menter Shear Stress Transport k-ω two-equation model, and an explicit algebraic stress k-ω formulation. Effects of grid resolution and upwinding scheme were also considered. The results from the CFD calculations are compared to particle image velocimetry (PIV) data from the experiments. As expected, turbulence model effects dominated the accuracy of the solutions with upwinding scheme selection indicating minimal effects.

RANS Modeling of Benchmark Shockwave / Boundary Layer Interaction Experiments

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Outline

- U. Michigan Case 1 – 7.75^o Shock Generator, Mach 2.75
  – Grid and solution details with SST turbulence model
  – Comparisons of CFD solutions with experiment using SST, SA, ASM turbulence models
  – Upwind scheme comparisons with SST
  – Grid resolution comparisons with SST
- U. Michigan Case 1-3 (7.75^o, 10^o, and 12^o) U-velocity variations, all Mach 2.75
- UFAST*, 8^o Shock Generator, Mach 2.25
  – Grid and solution details with SST turbulence model
  – Comparisons of CFD solutions with experiment using SST, SA, ASM turbulence models

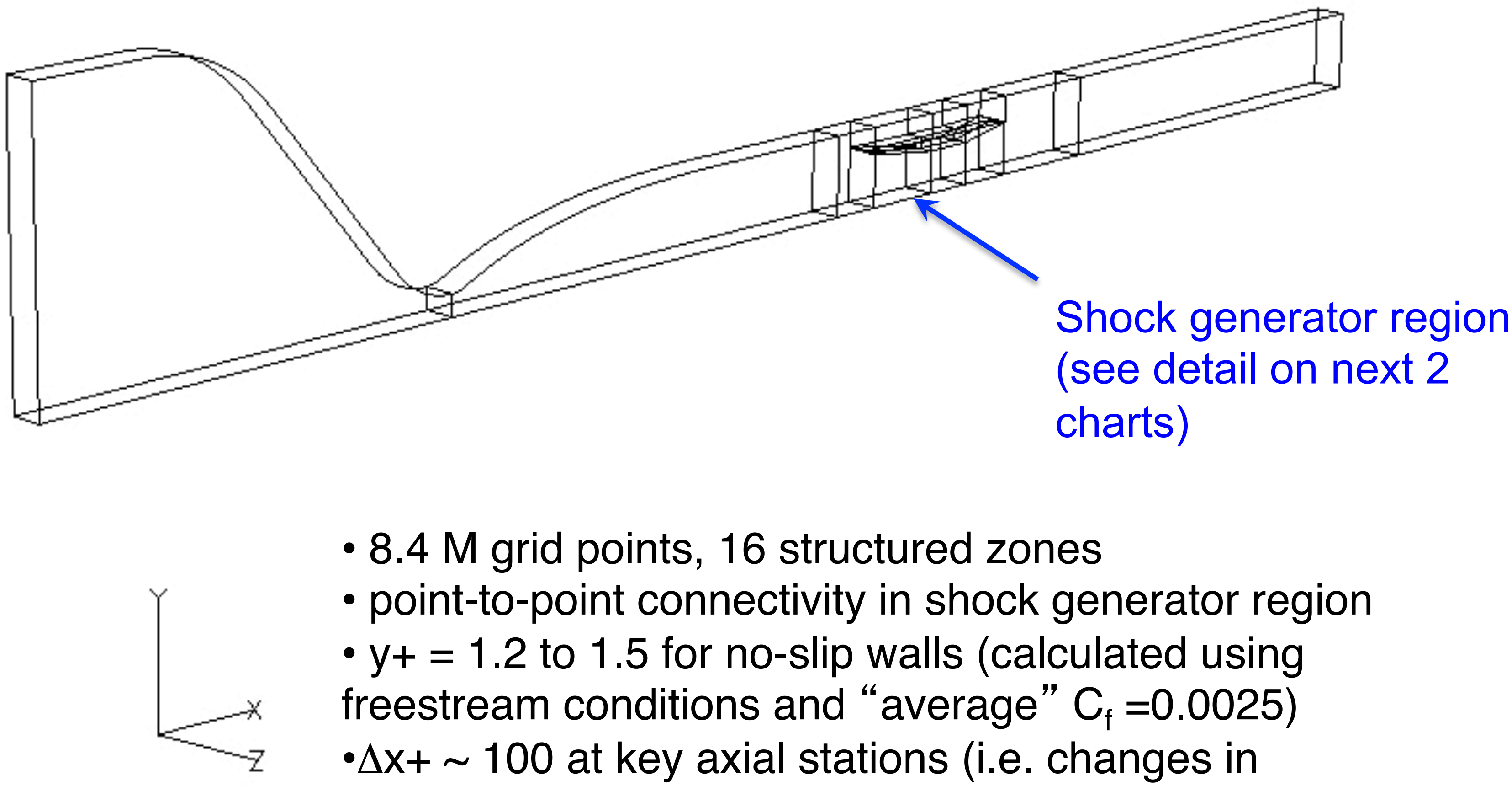
**Unsteady effects in shock wave induced separation, Institut Universitaire des Systèmes Thermiques Industriels*

Flow Solver Specifics

- Wind-US, version 2.0
- Structured grids utilized, grids built with Gridgen
- Turbulence Models:
  - **SST* (Menter Shear Stress Transport)**
  - SA (Spalart Allmaras)
  - ASM (built upon Menter BSL k-ω)
- Upwind Schemes (all 2nd order): **Roe***, Van-Leer, HLLC

** items shown in bold are default when not otherwise noted.*

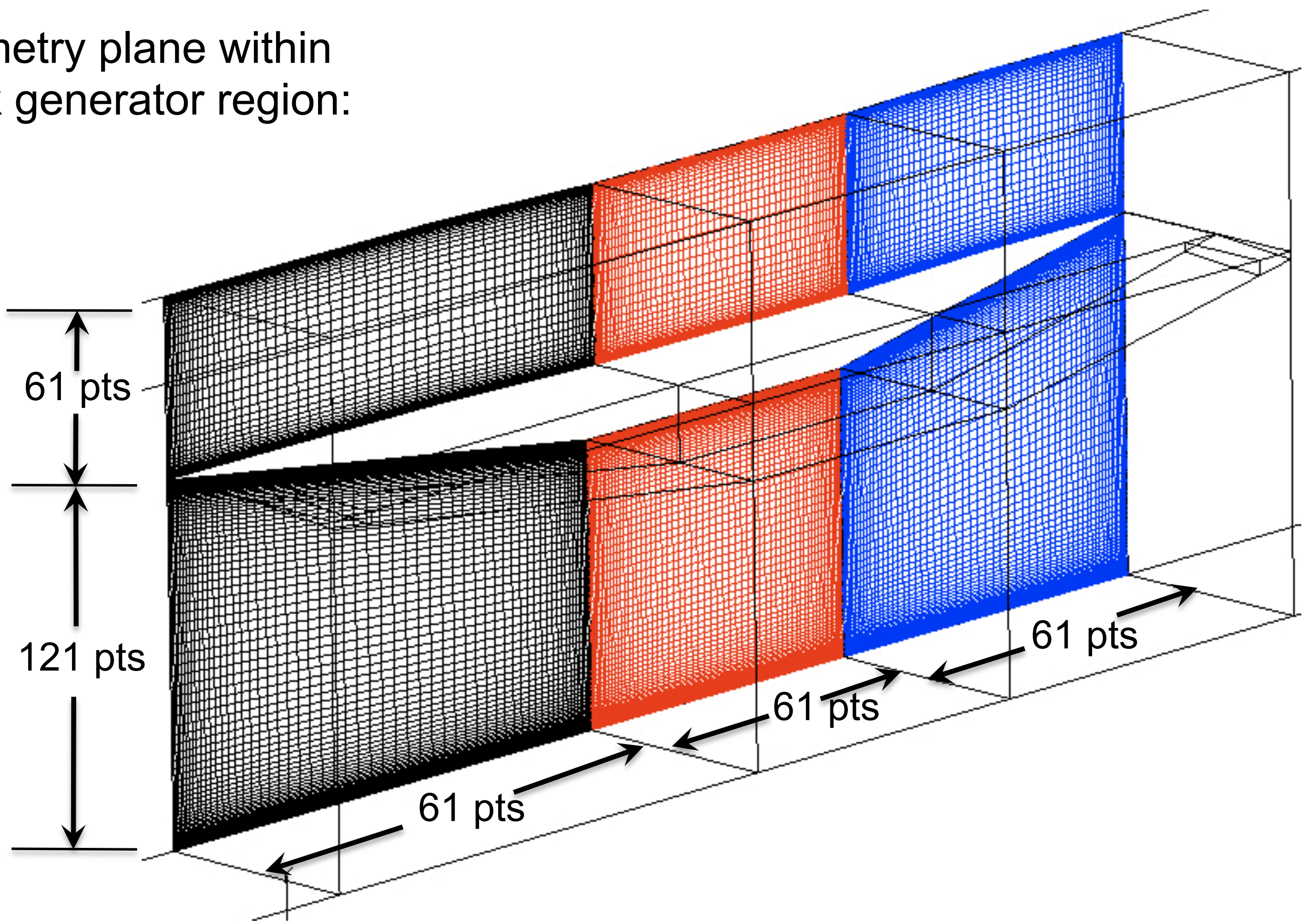
UM Cases 1-3 Grid (1 of 3)



- 8.4 M grid points, 16 structured zones
- point-to-point connectivity in shock generator region
- y+ = 1.2 to 1.5 for no-slip walls (calculated using freestream conditions and "average" C_f =0.0025)
- Δx+ ~ 100 at key axial stations (i.e. changes in geometry)
- Grids smooth (no abrupt changes in packing) in shock generator region, within & across zones

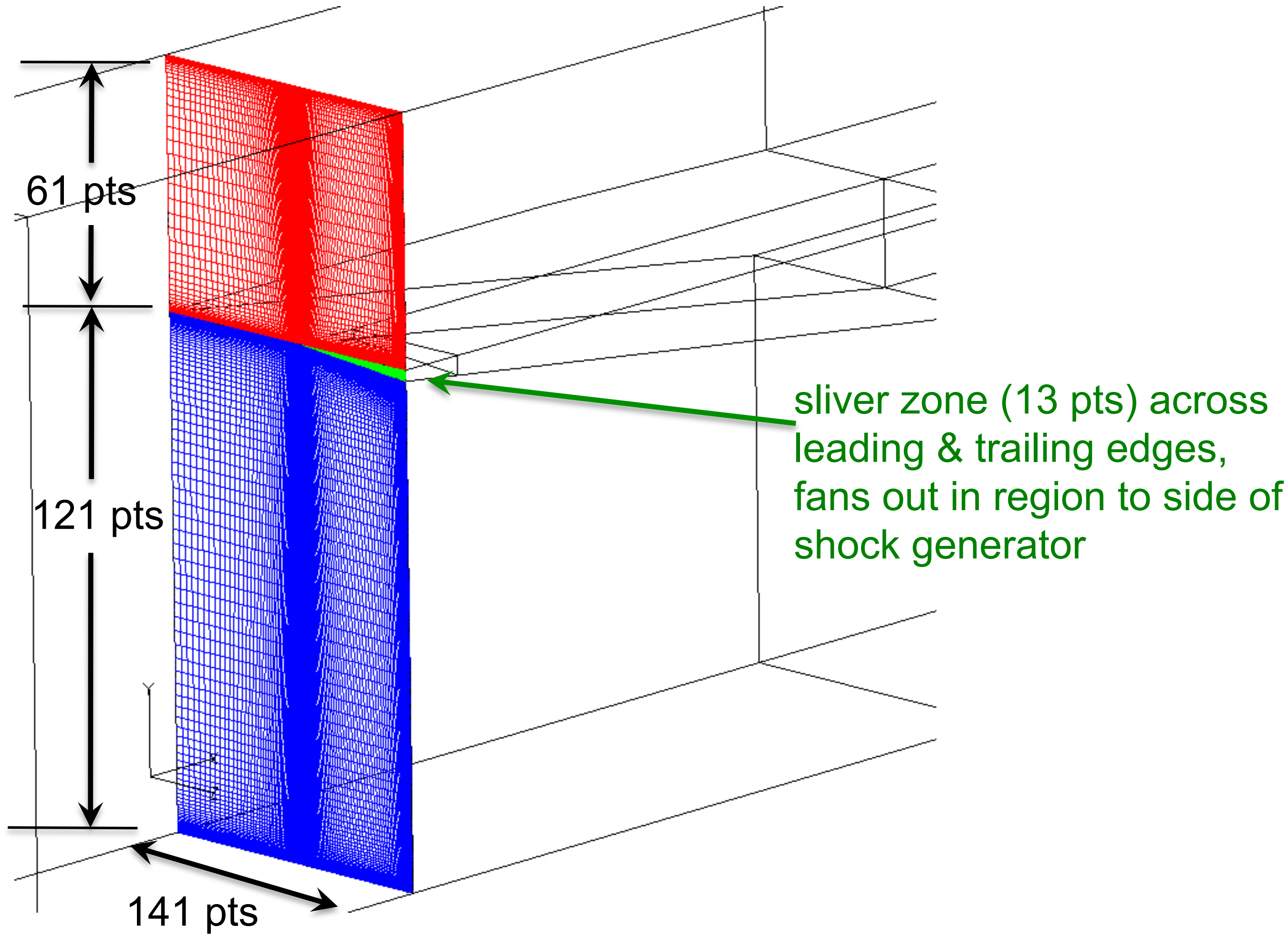
UM Cases 1-3 Grid (2 of 3)

Symmetry plane within shock generator region:



UM Cases 1-3 Grid (3 of 3)

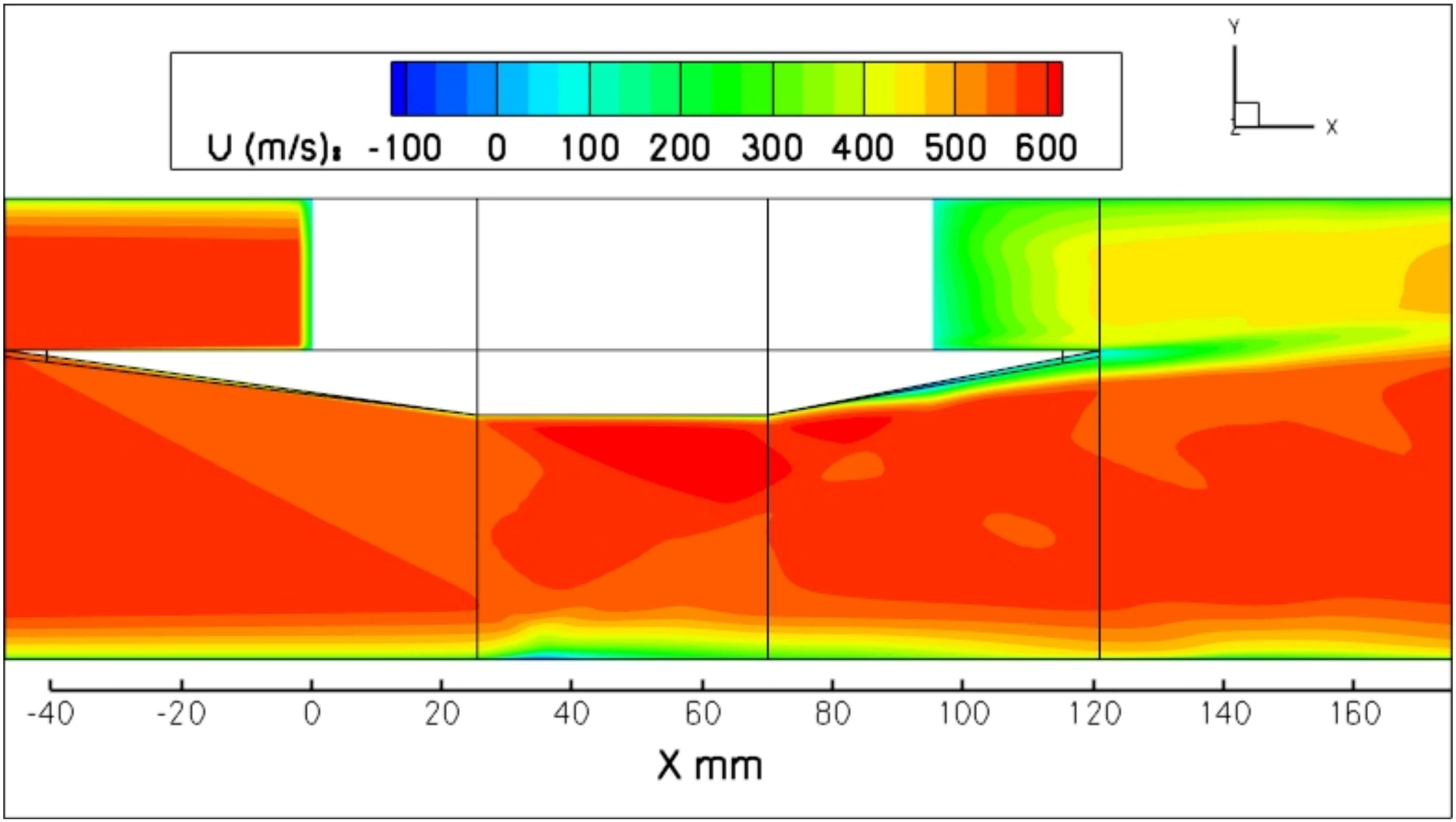
Entrance plane to shock generator region:



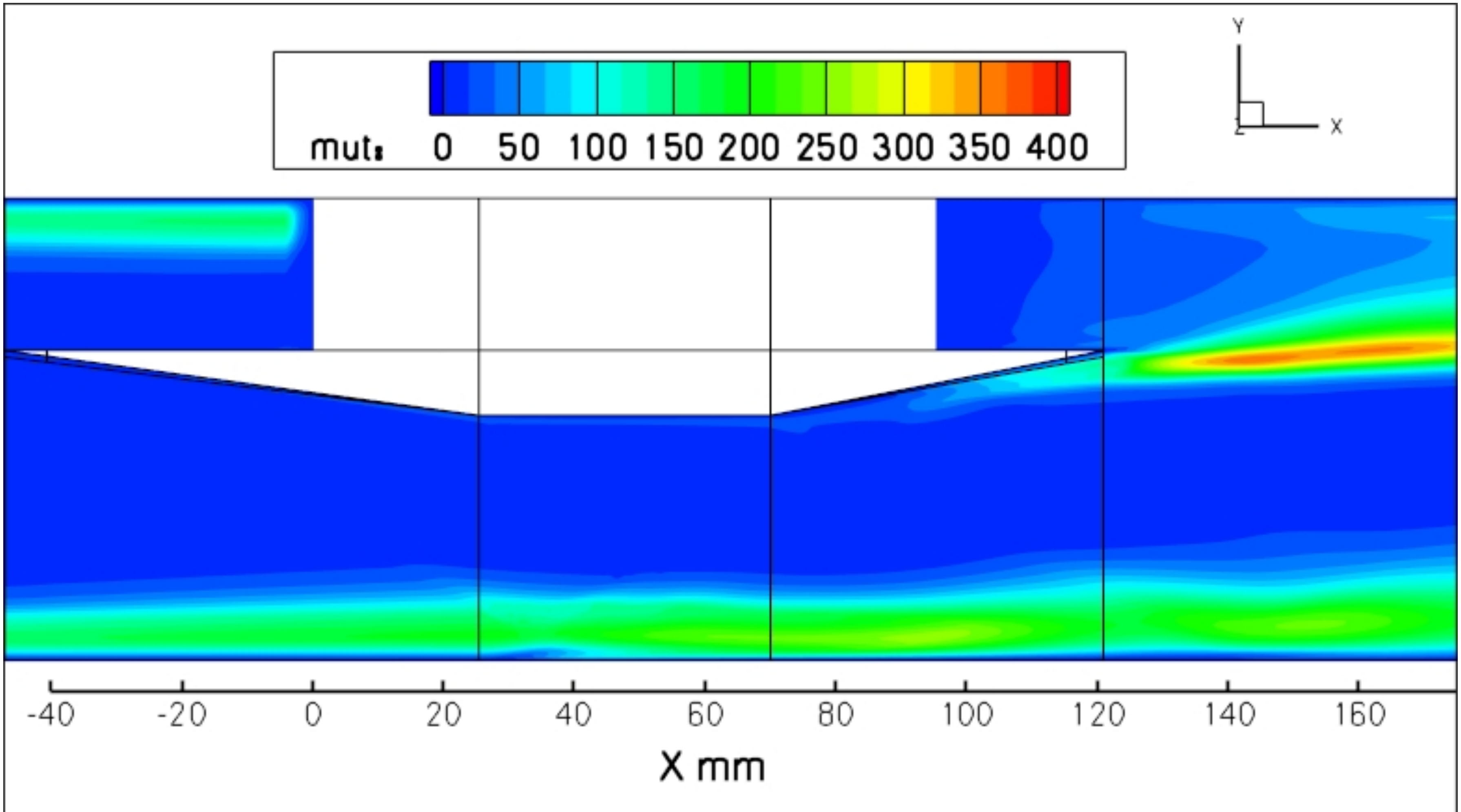
U. Michigan Case 1 – 7.75^o Shock Generator, Mach 2.75

Comparisons of CFD solutions with experiment
using SST, SA, ASM turbulence models

U Velocities Along Symmetry Plane (7.75 degree wedge)

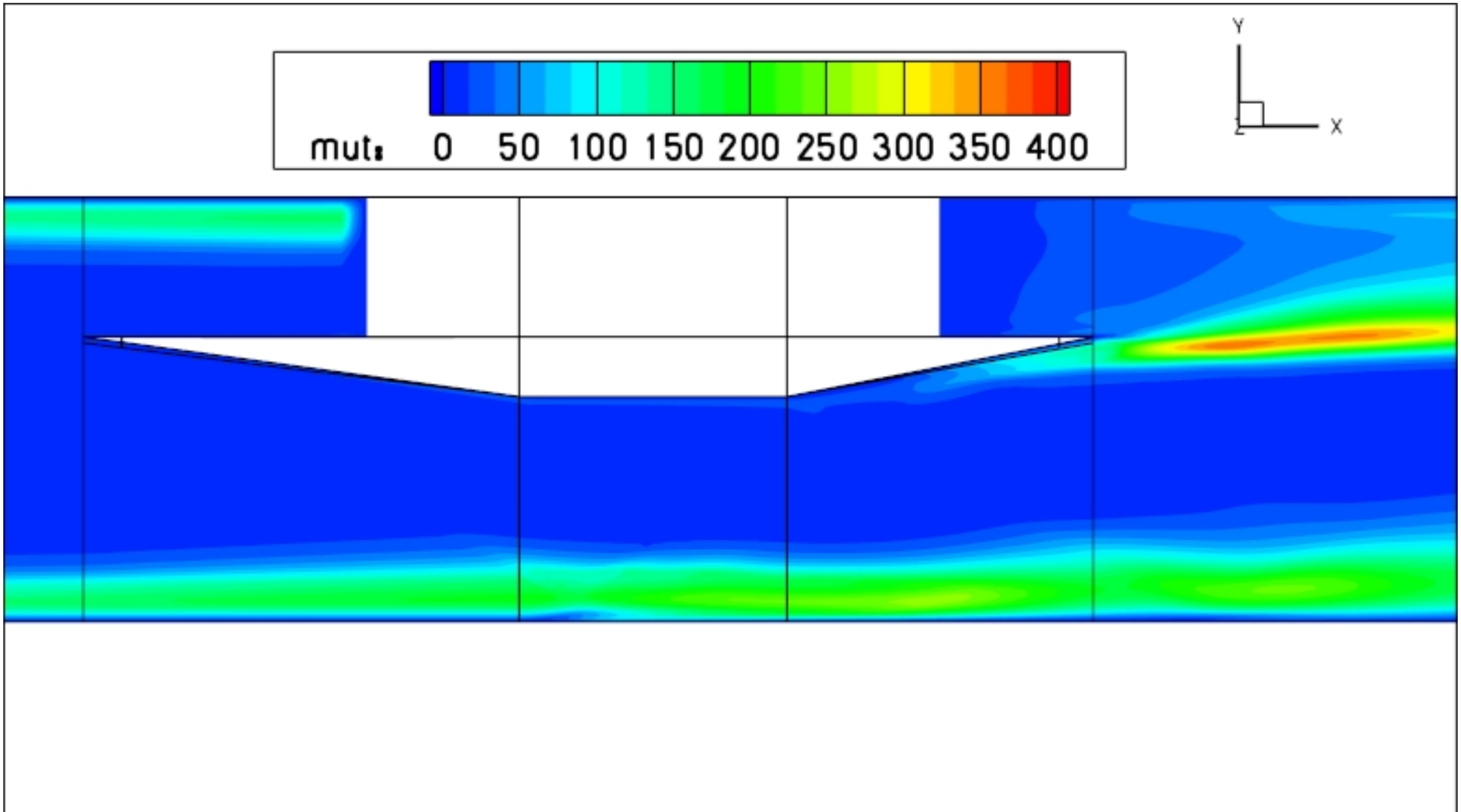


Eddy Viscosity Along Symmetry Plane (7.75 degree wedge)



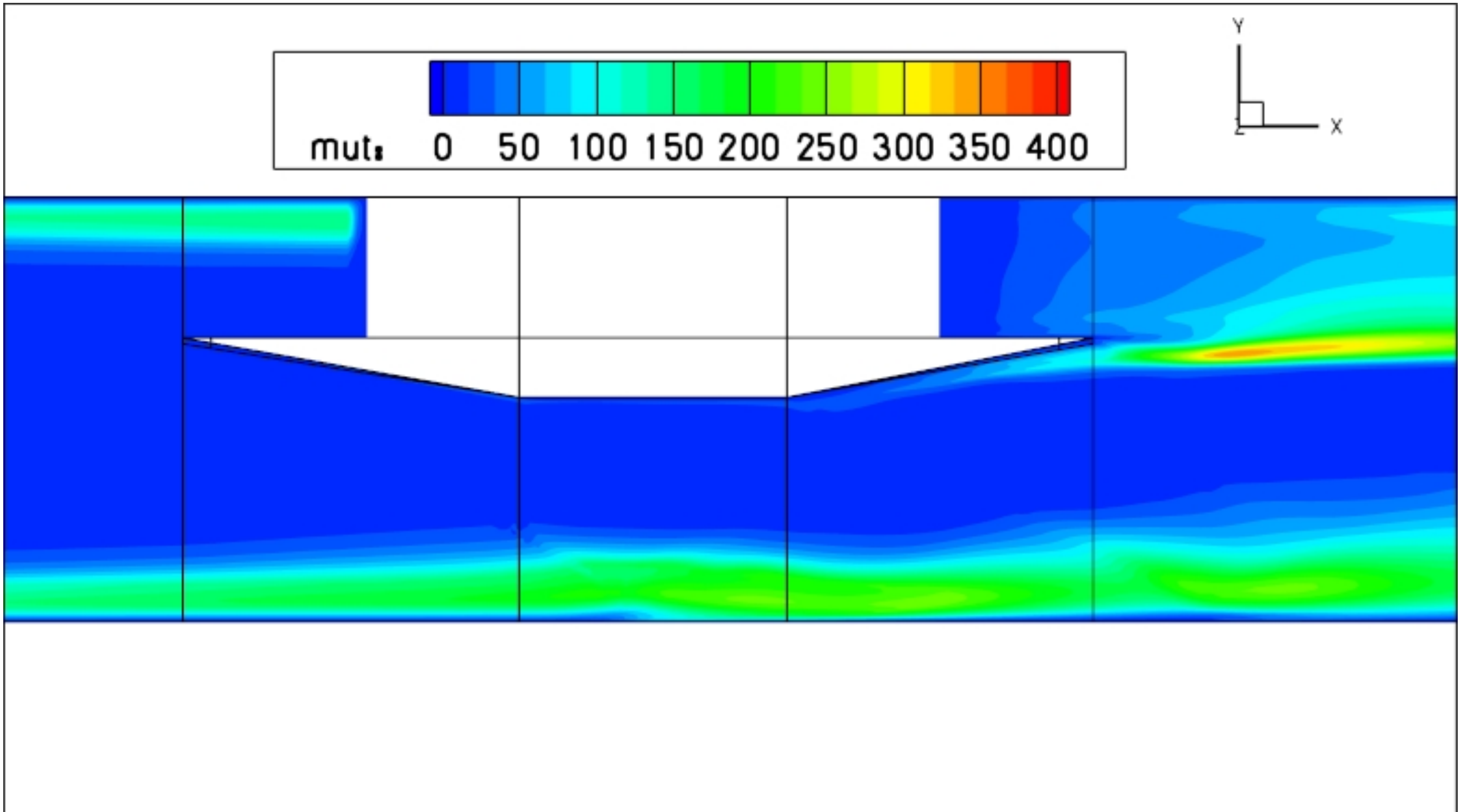
* *Contours shown are μ_t/μ_{ref} and are clipped on high end.*

Eddy Viscosity Along Symmetry Plane (7.75 degree wedge) Old



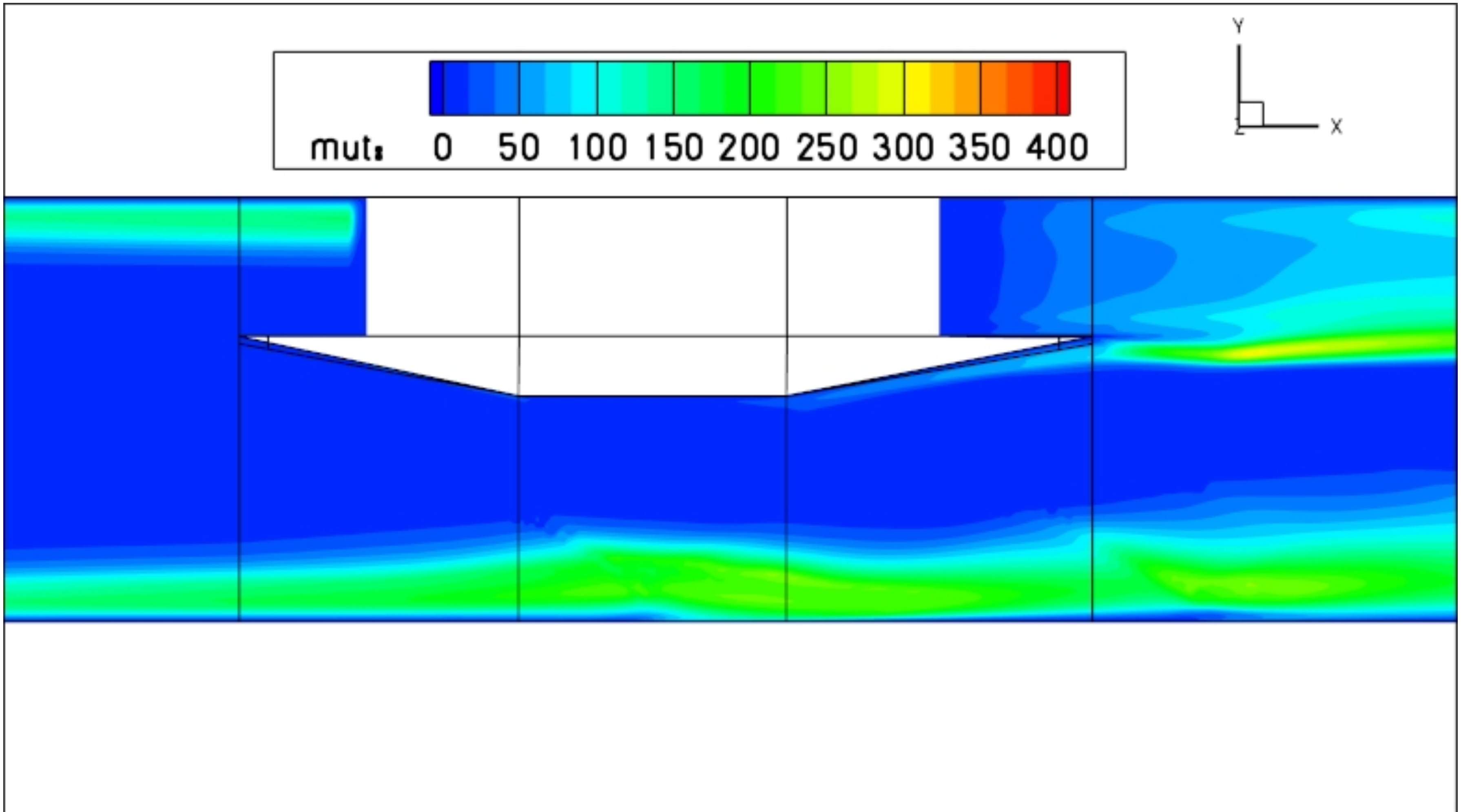
* *Contours shown are* μ_t / μ_{ref} *and are clipped on high end.*

Eddy Viscosity Along Symmetry Plane (10 degree wedge) NEW



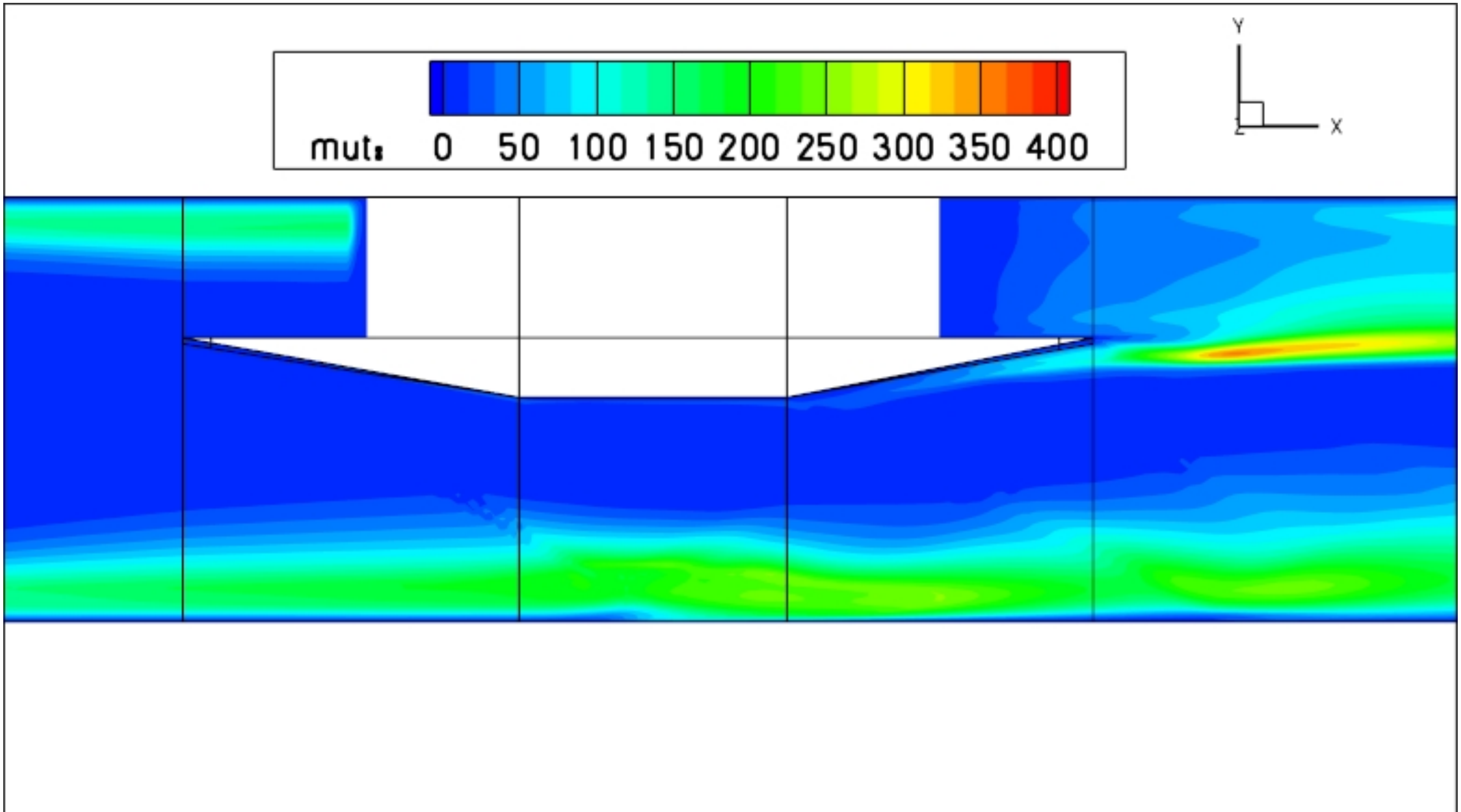
* Contours shown are μ_t/μ_{ref} and are clipped on high end.

Eddy Viscosity Along Symmetry Plane (12 degree wedge) Old



** Contours shown are μ_t / μ_{ref} and are clipped on high end.*

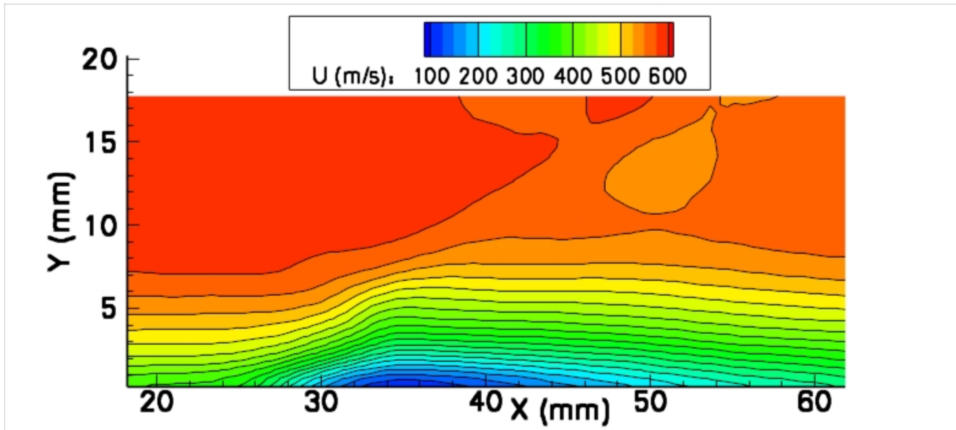
Eddy Viscosity Along Symmetry Plane (10 degree wedge) Old



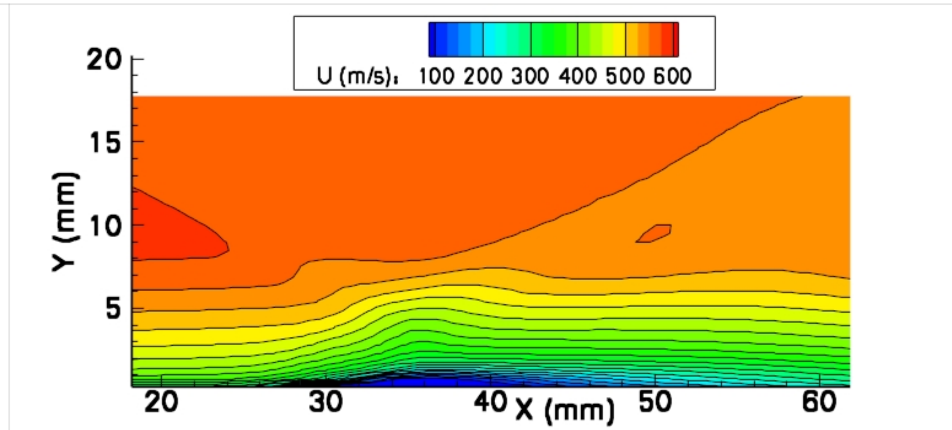
* *Contours shown are μ_t / μ_{ref} and are clipped on high end.*

U Velocity Contours

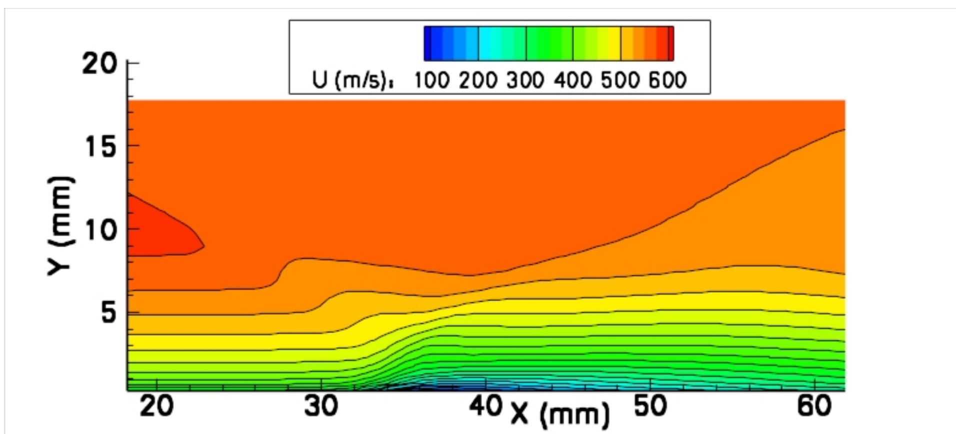
Experiment:



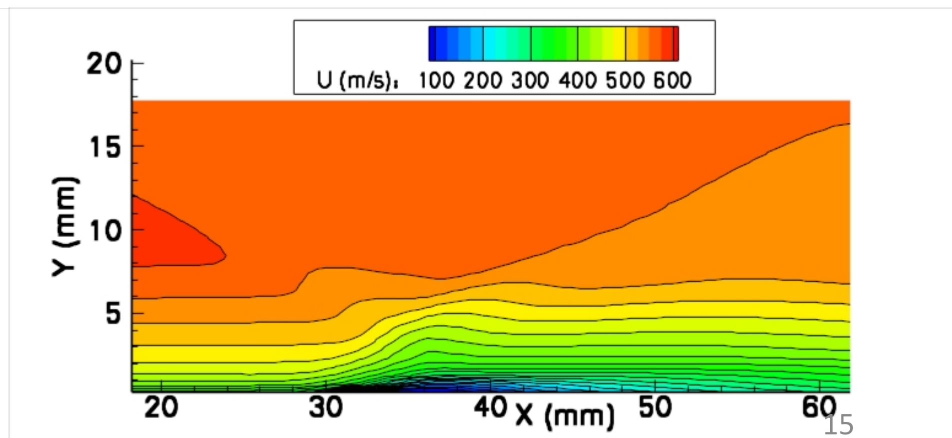
SST:



SA:

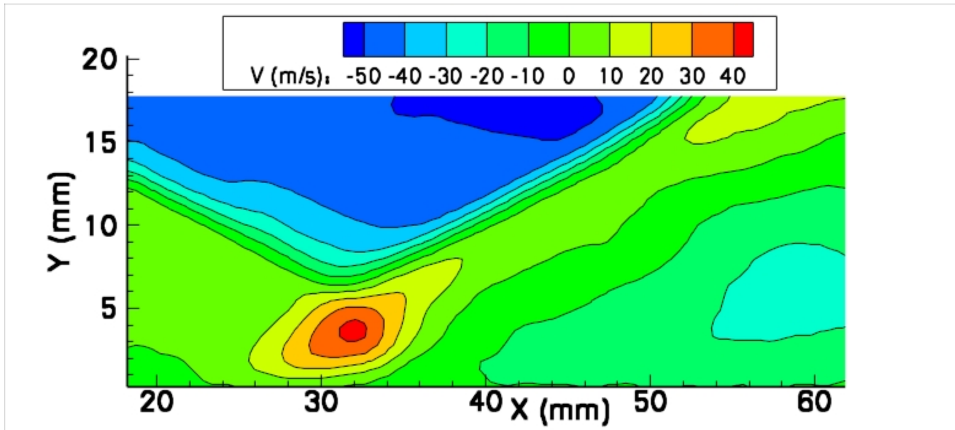


ASM:

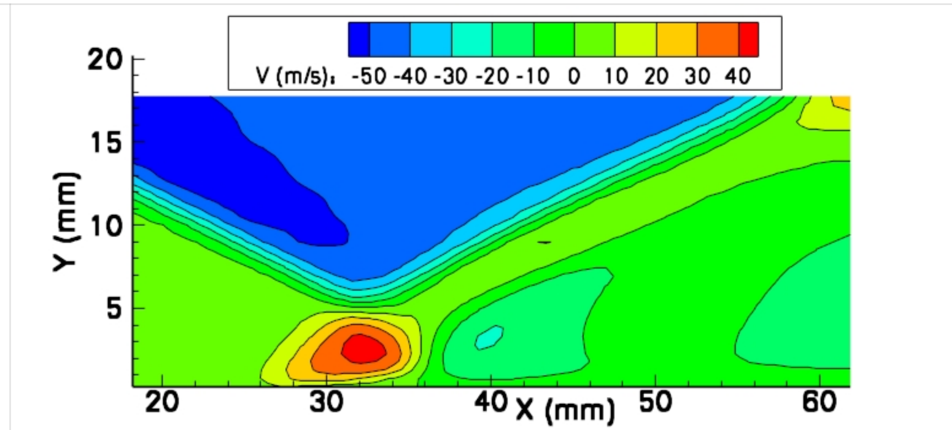


V Velocity Contours

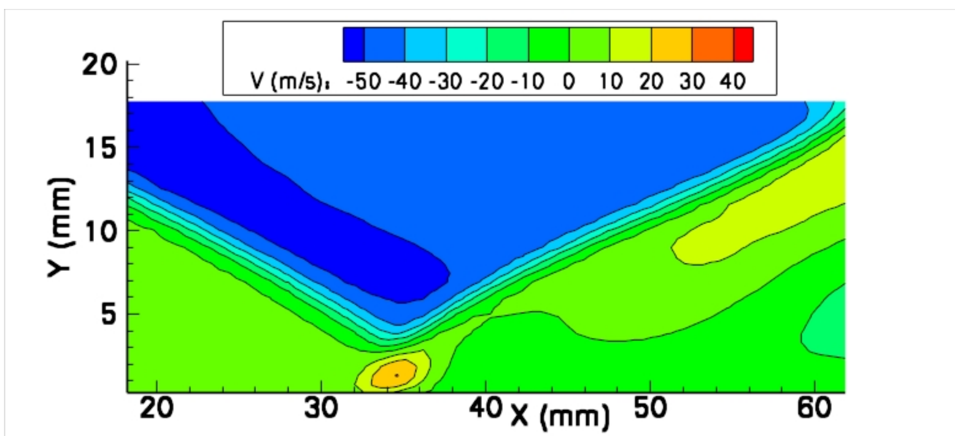
Experiment:



SST:



SA:



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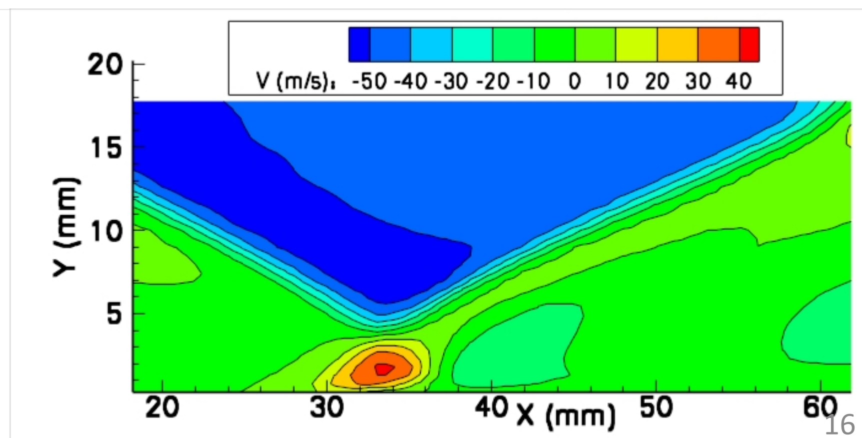
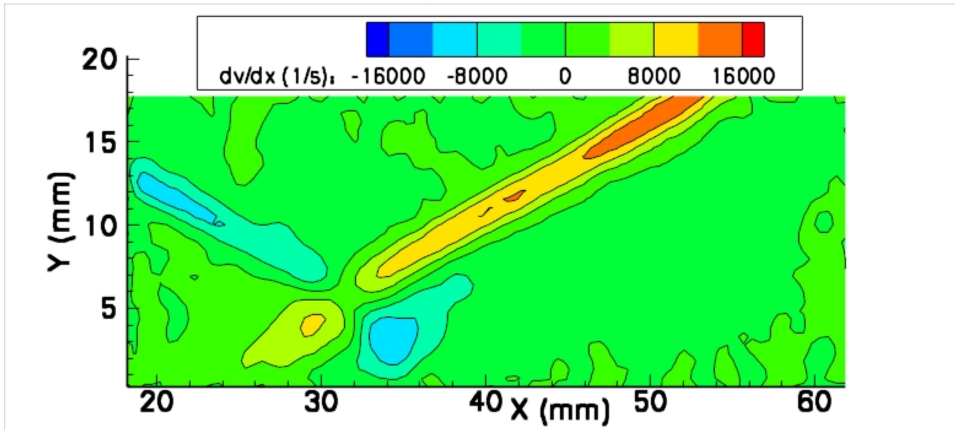
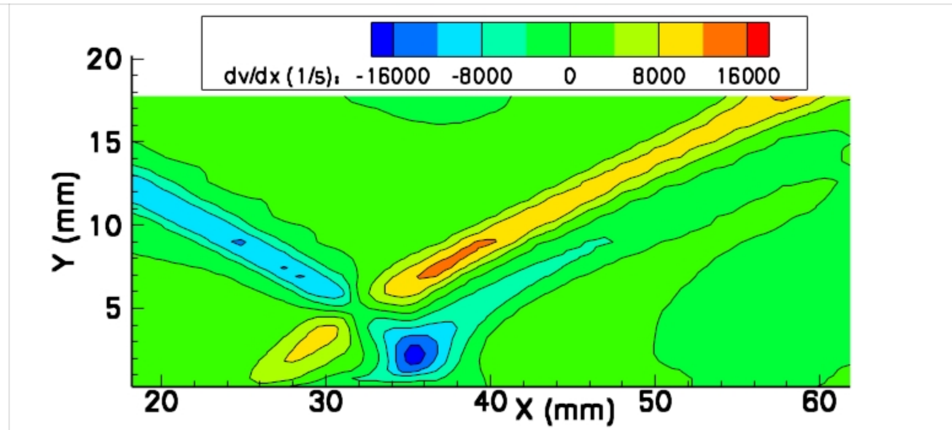


dV/dX Contours

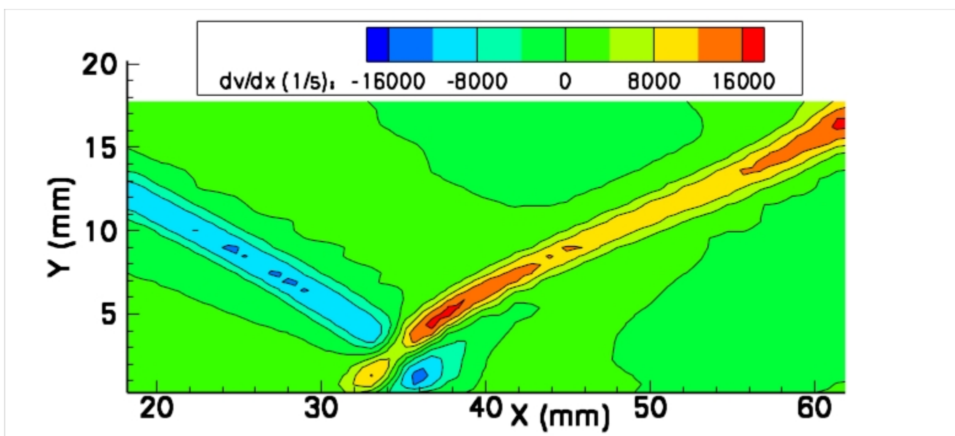
Experiment:



SST:



SA:



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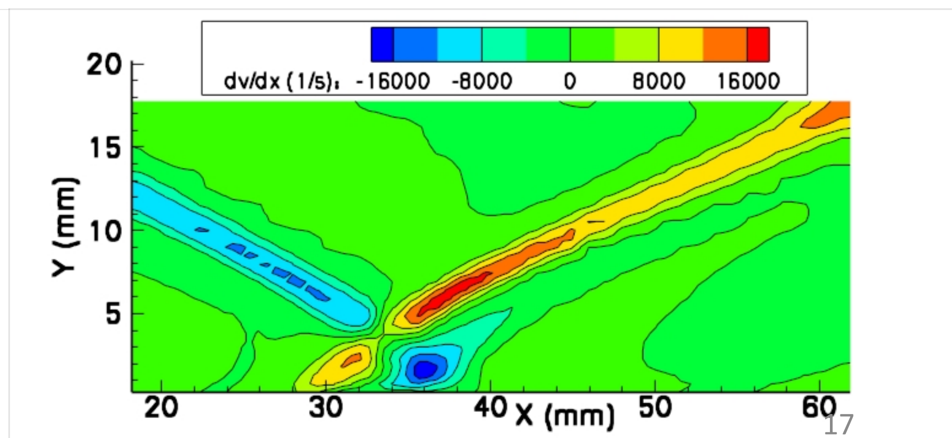
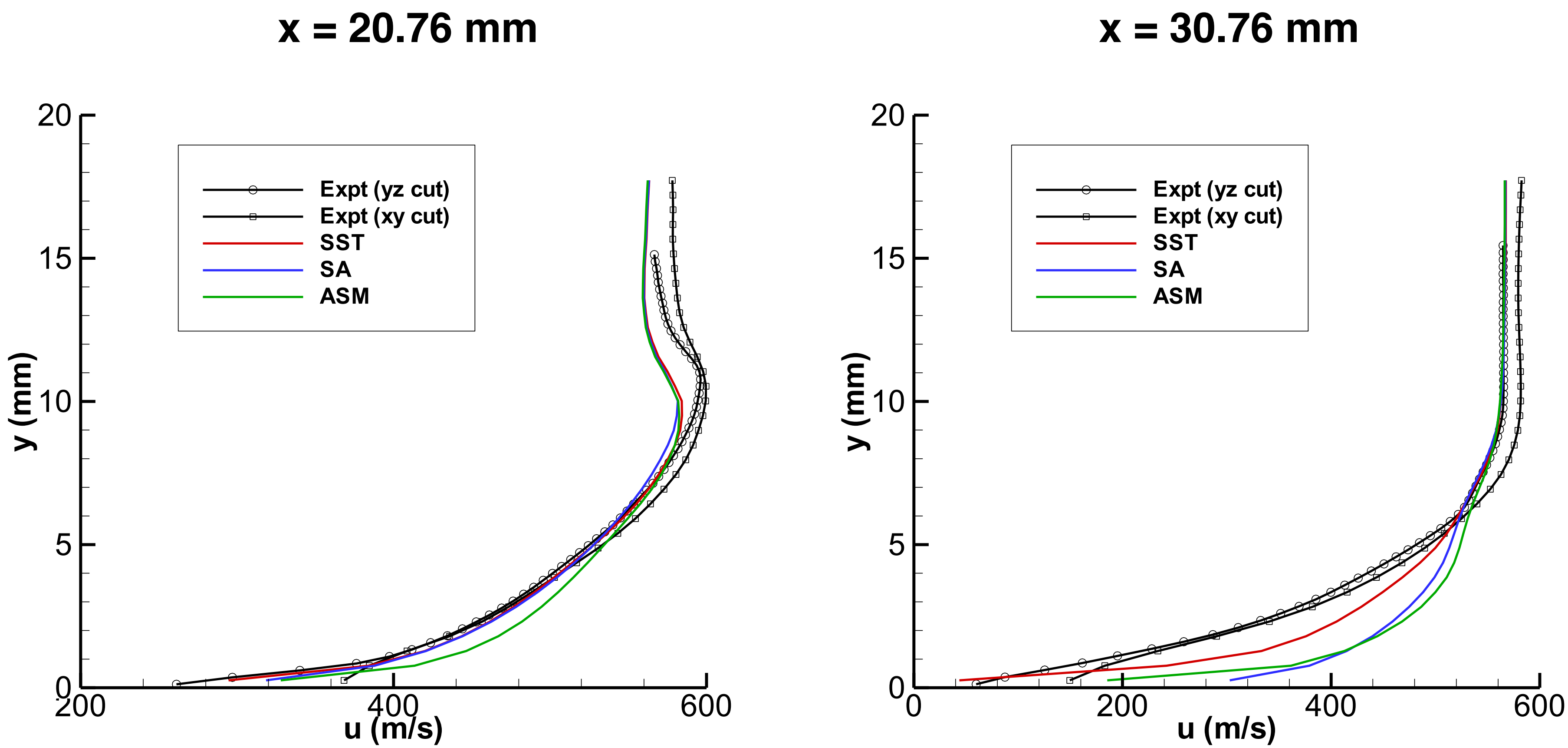
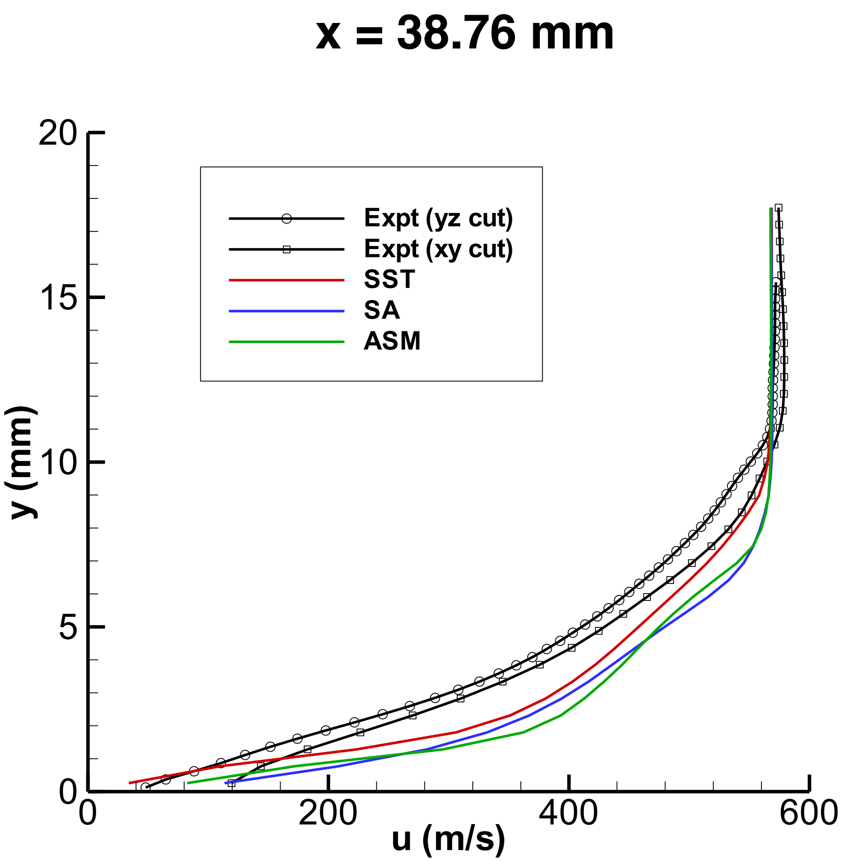
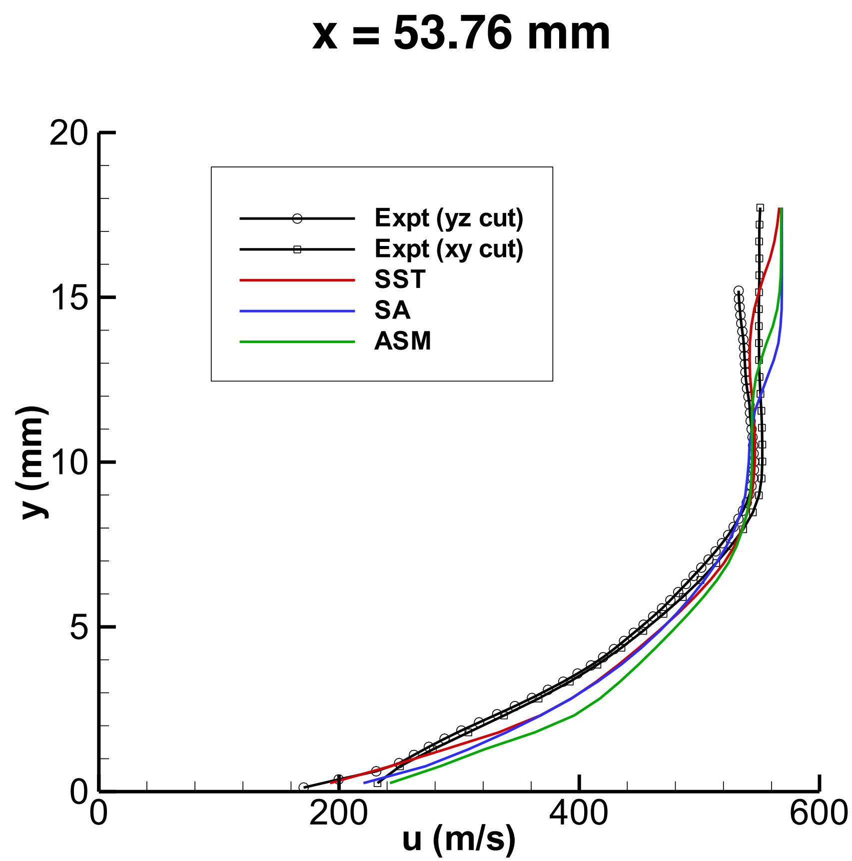


U Velocity Profiles



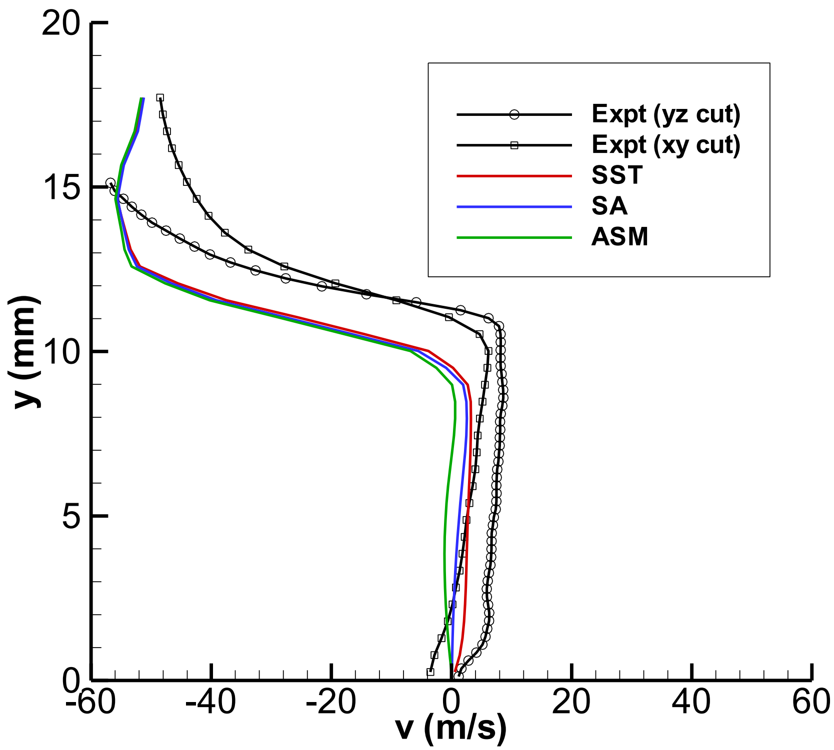
U Velocity Profiles



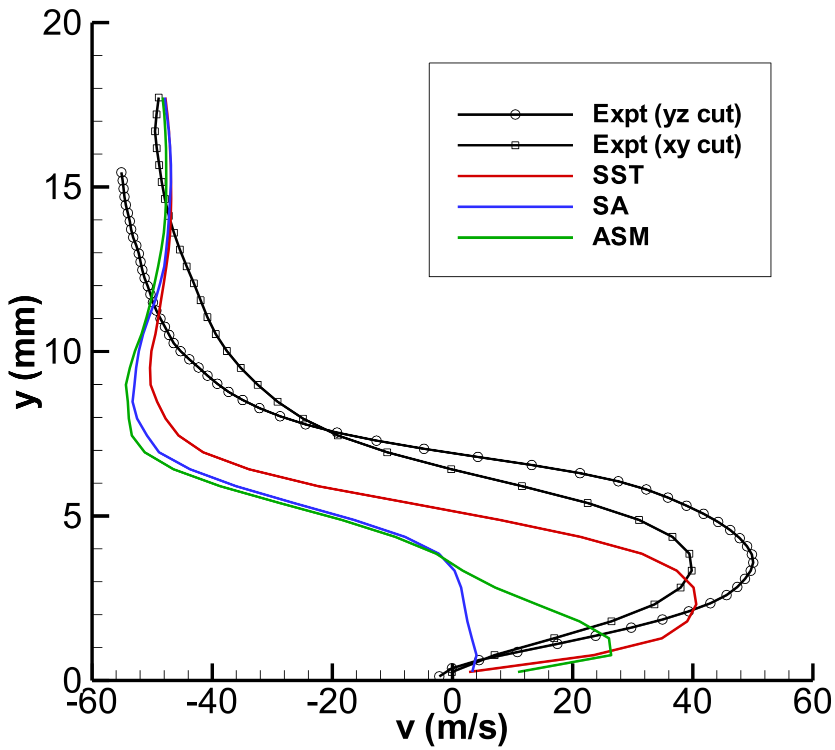


V Velocity Profiles

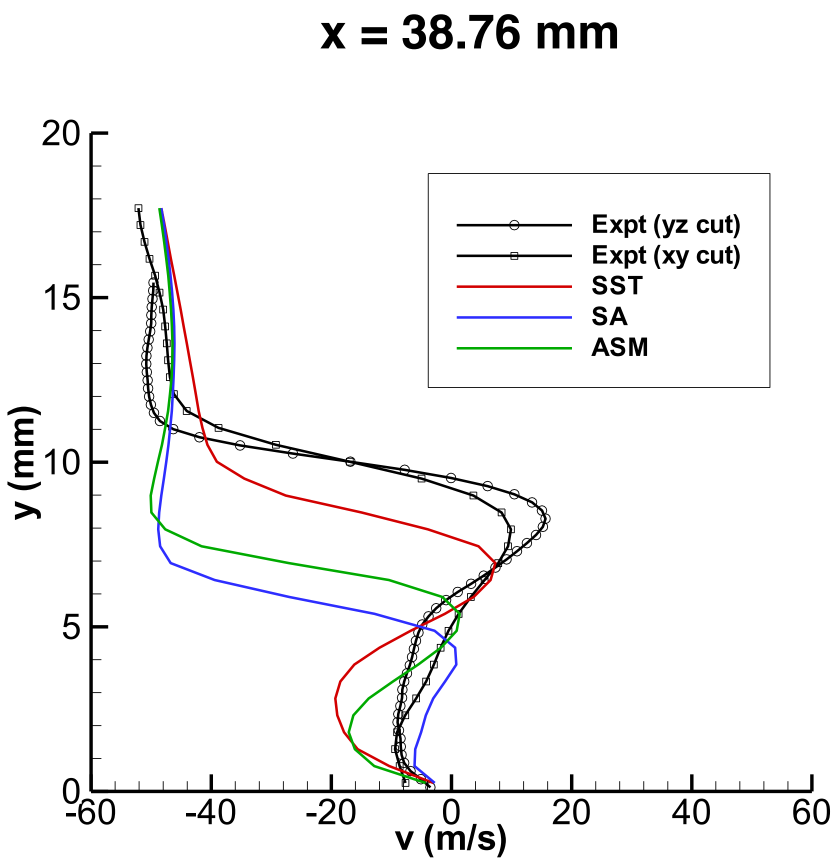
x = 20.76 mm

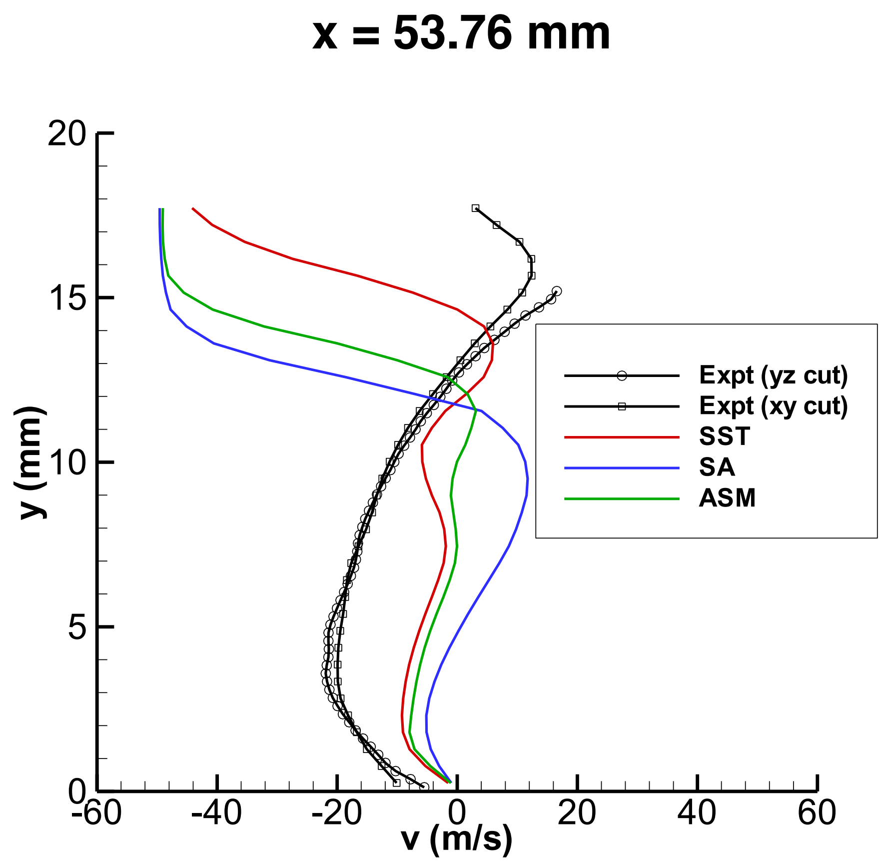


x = 30.76 mm



V Velocity Profiles





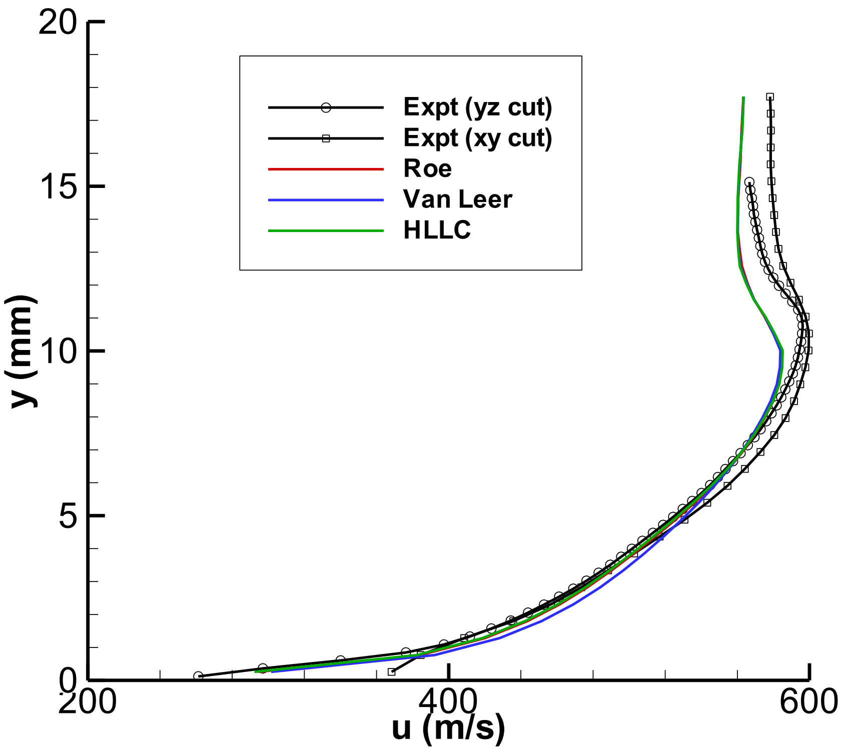
U. Michigan Case 1 – 7.75° Shock Generator, Mach 2.75

Upwind scheme comparisons with SST

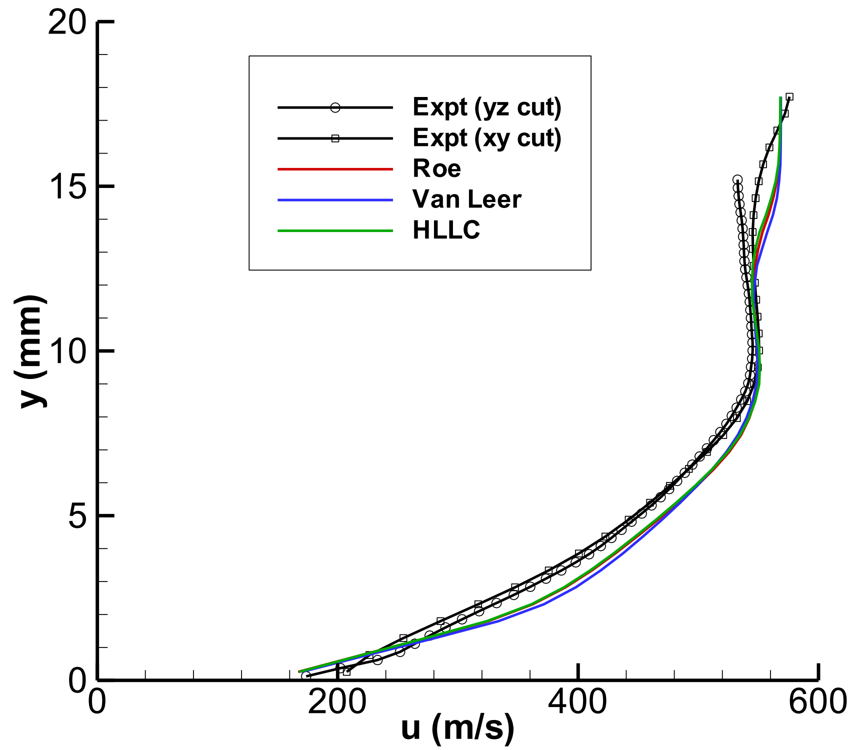
U Velocity Profiles

(Effect of Upwind Scheme – all SST Turbulence Model)

x = 20.76 mm



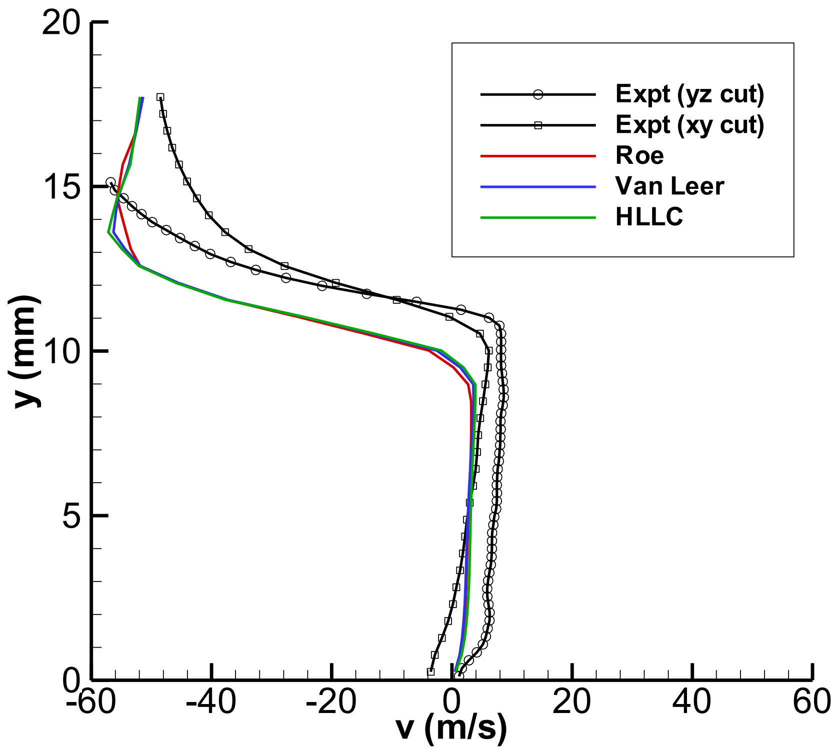
x = 53.76 mm



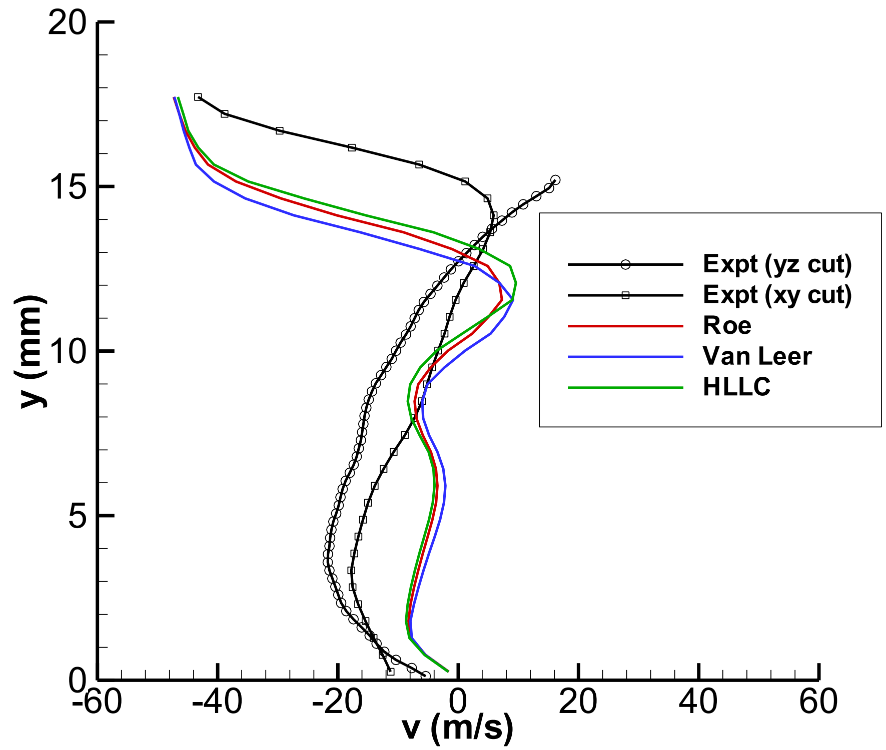
V Velocity Profiles

(Effect of Upwind Scheme – all SST Turbulence Model)

x = 20.76 mm



x = 53.76 mm

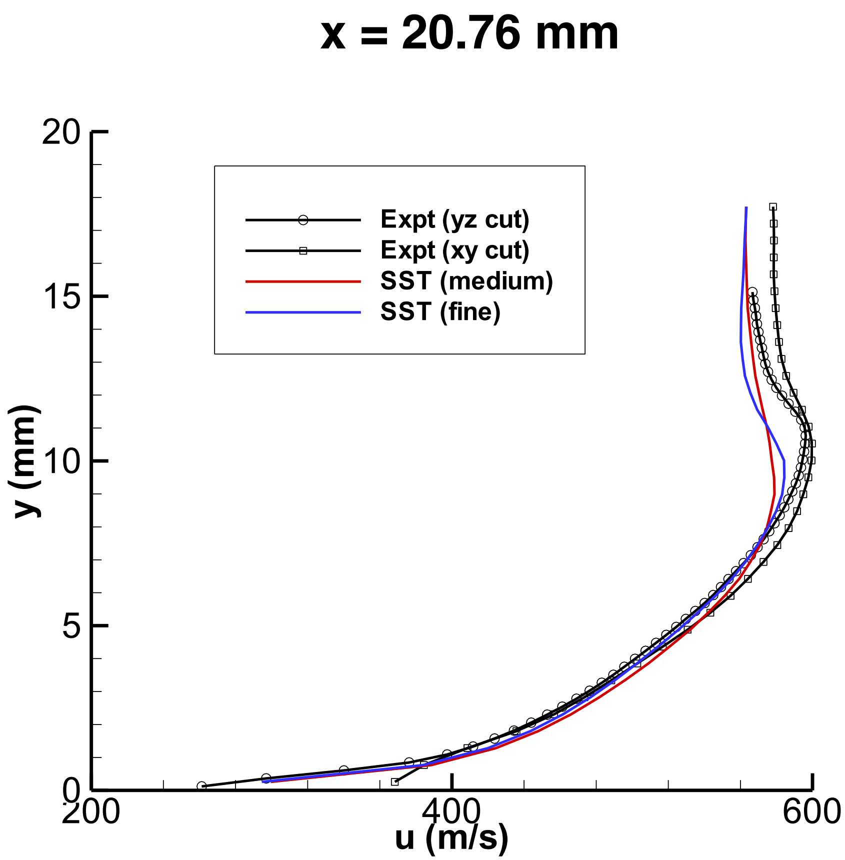


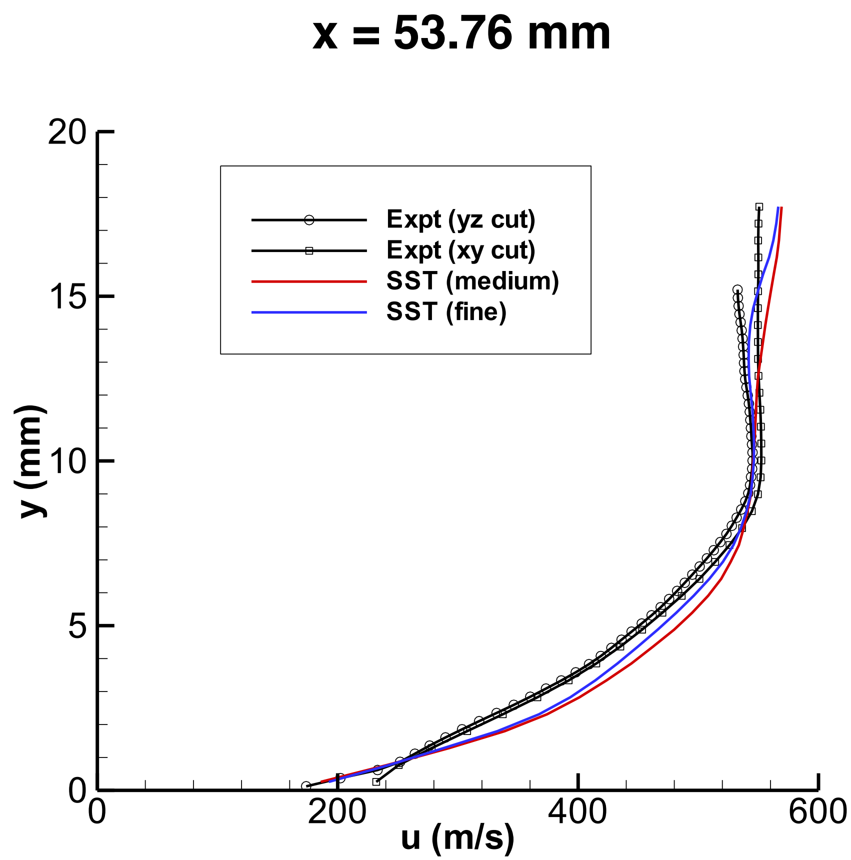
U. Michigan Case 1 – 7.75^{o} Shock Generator, Mach 2.75

Grid resolution comparisons with SST, Roe Scheme

- *Fine grid = 8.4 M points*
- *Medium grid = 1.1 M points (every other point utilized in each direction).*
- *Coarse (every 4th point in each direction) also available, but not shown in comparisons here.*

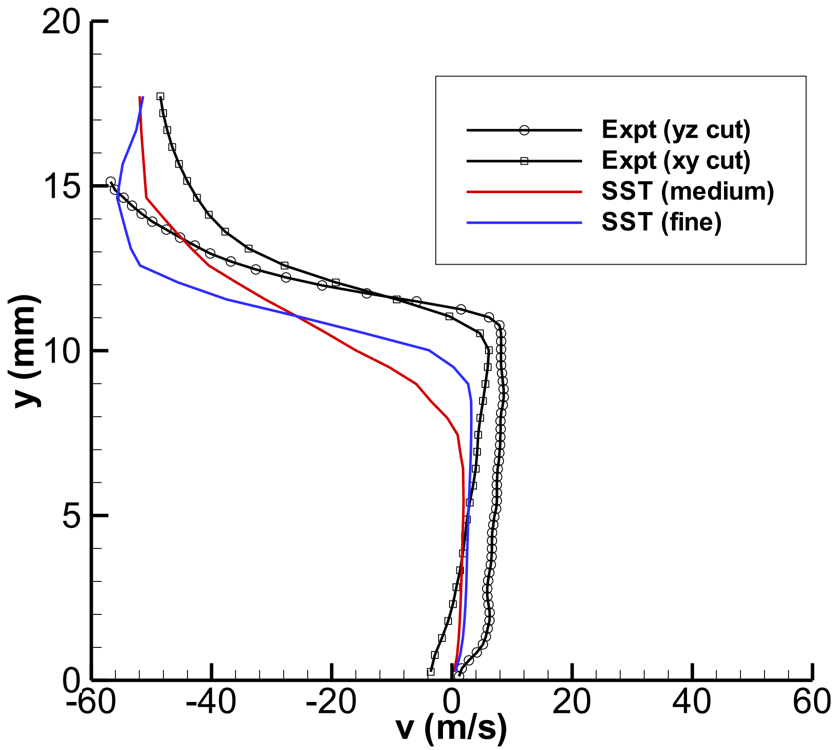
U Velocity Profiles



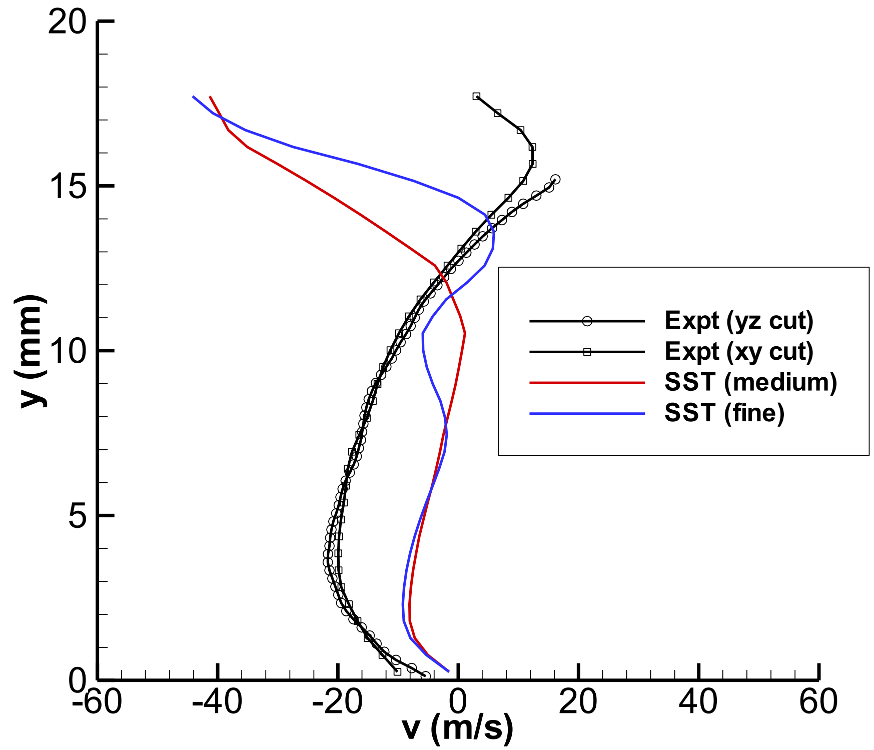


V Velocity Profiles

x = 20.76 mm



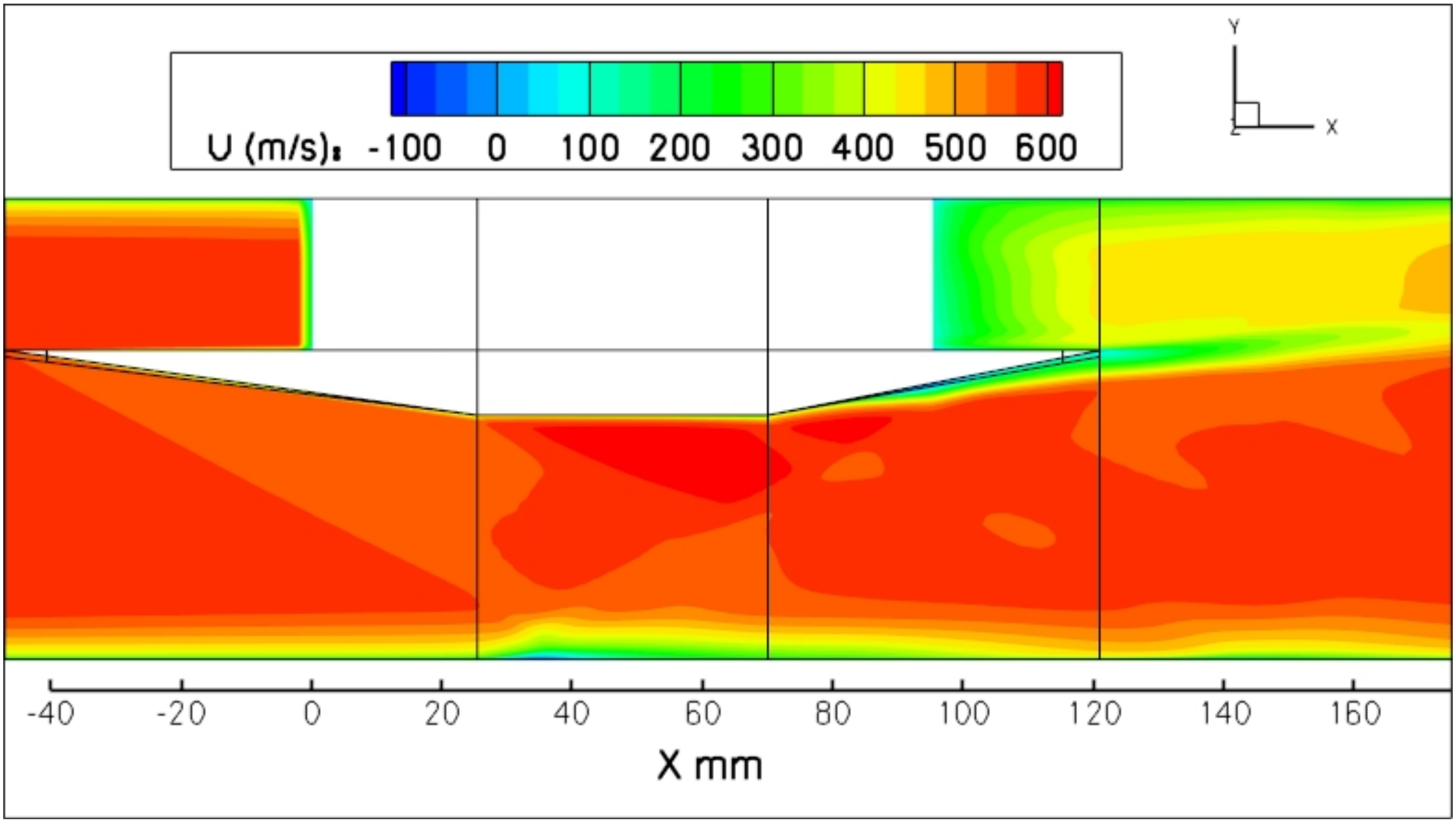
x = 53.76 mm



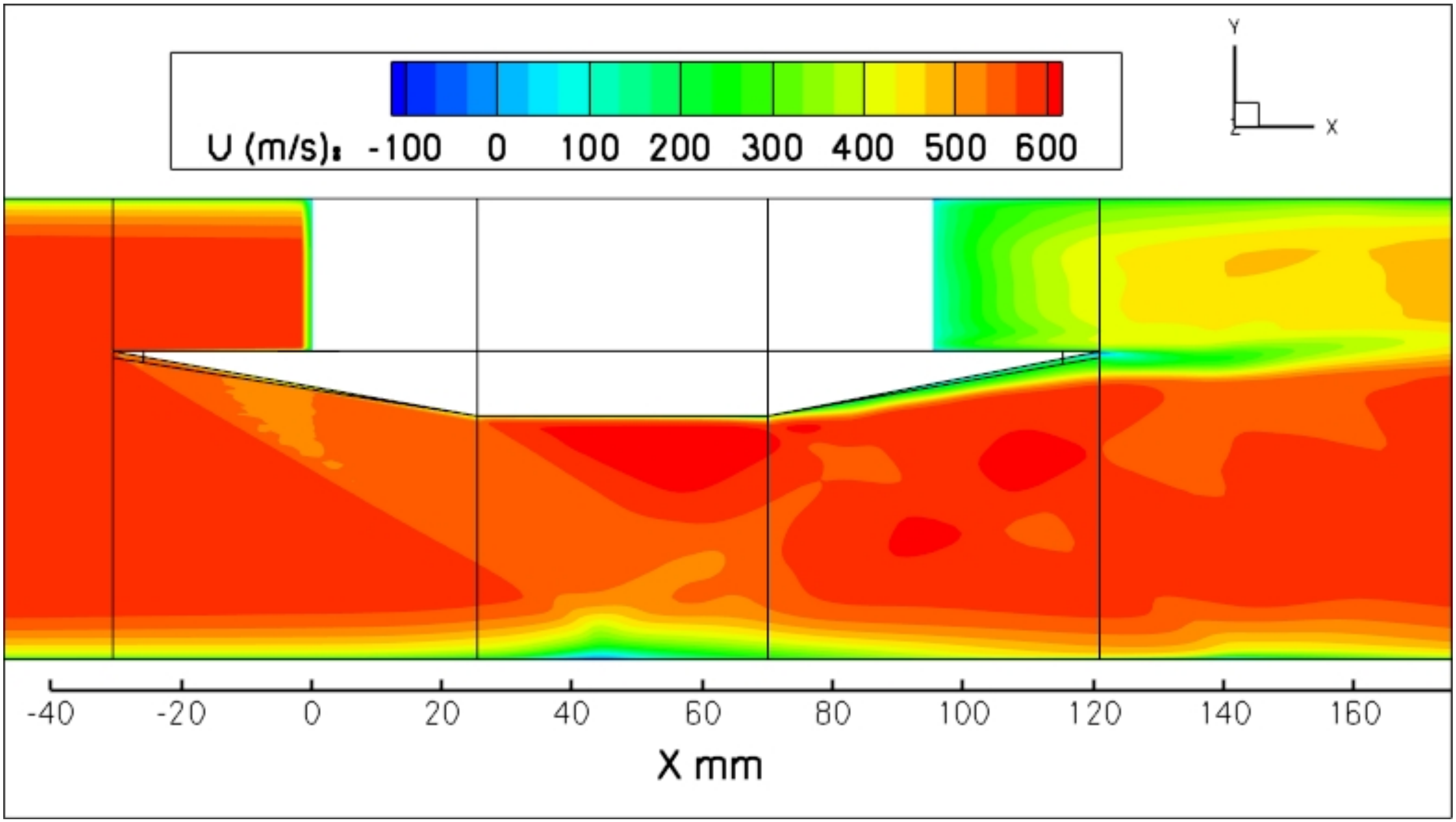
U. Michigan Case 1-3 (7.75^o, 10^o, and 12^o) Mach 2.75

U-velocity variations

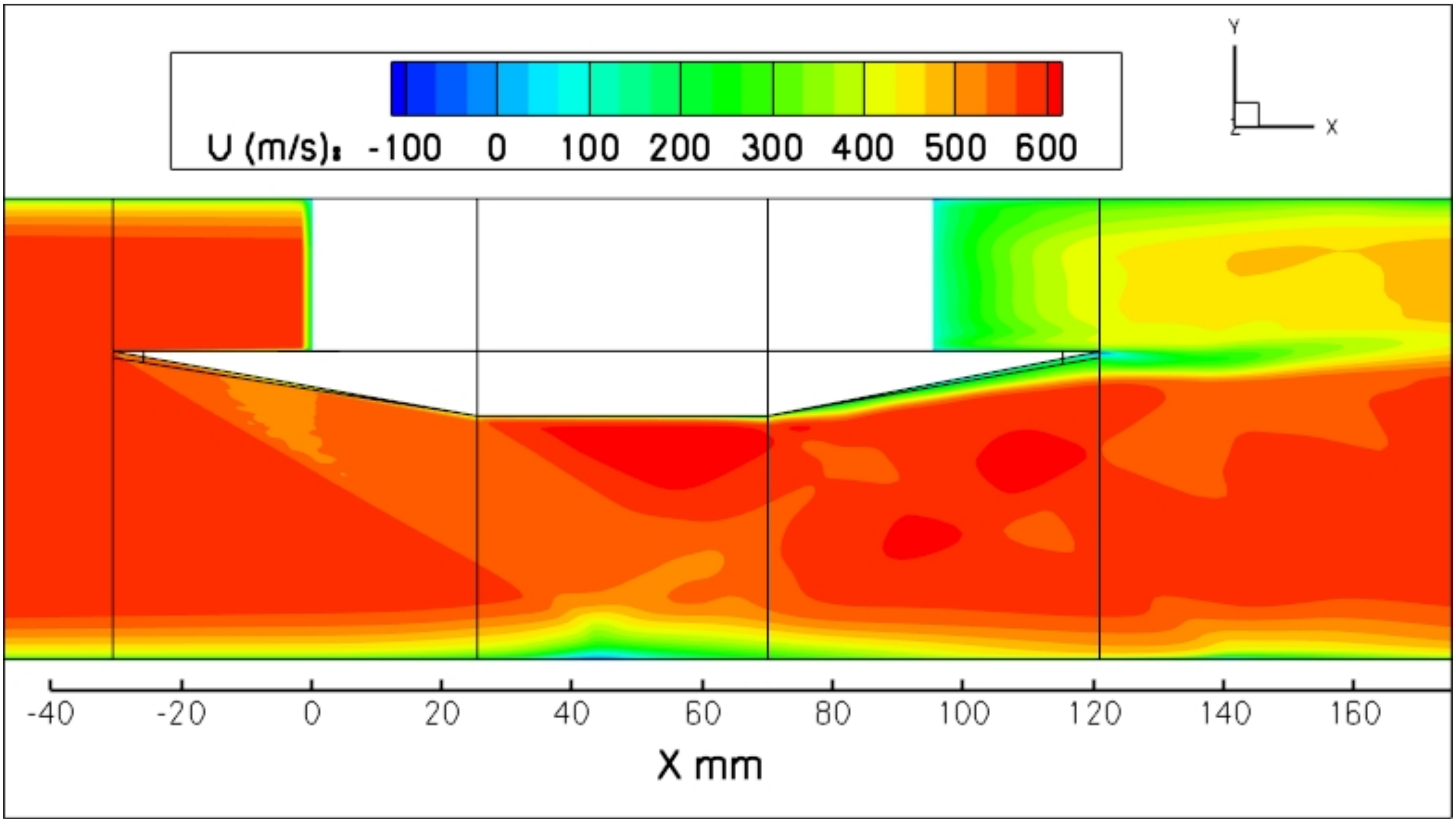
U Velocities Along Symmetry Plane (7.75 degree wedge)



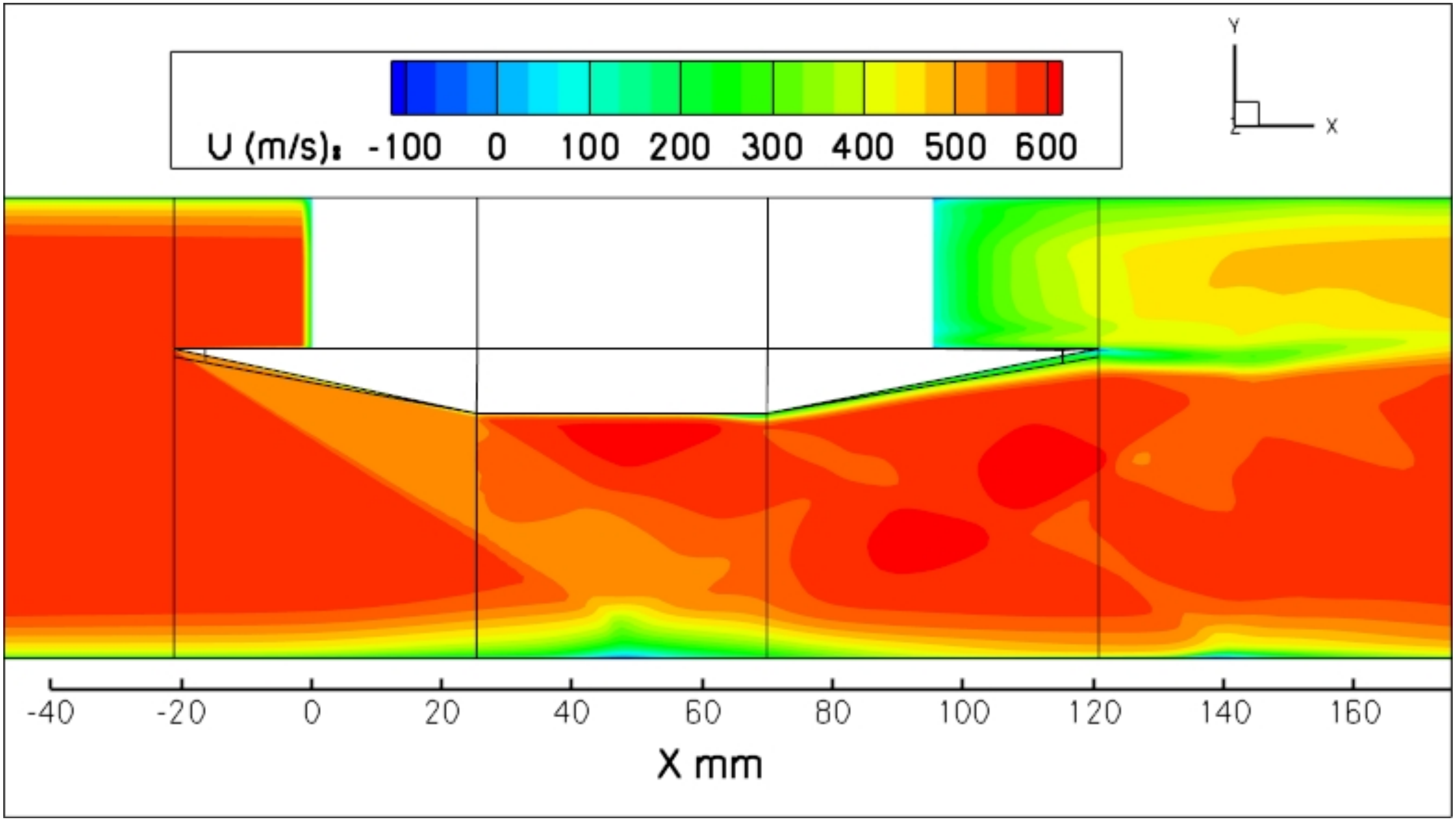
U Velocities Along Symmetry Plane (10 degree wedge)



U Velocities Along Symmetry Plane (10 degree wedge Manan)



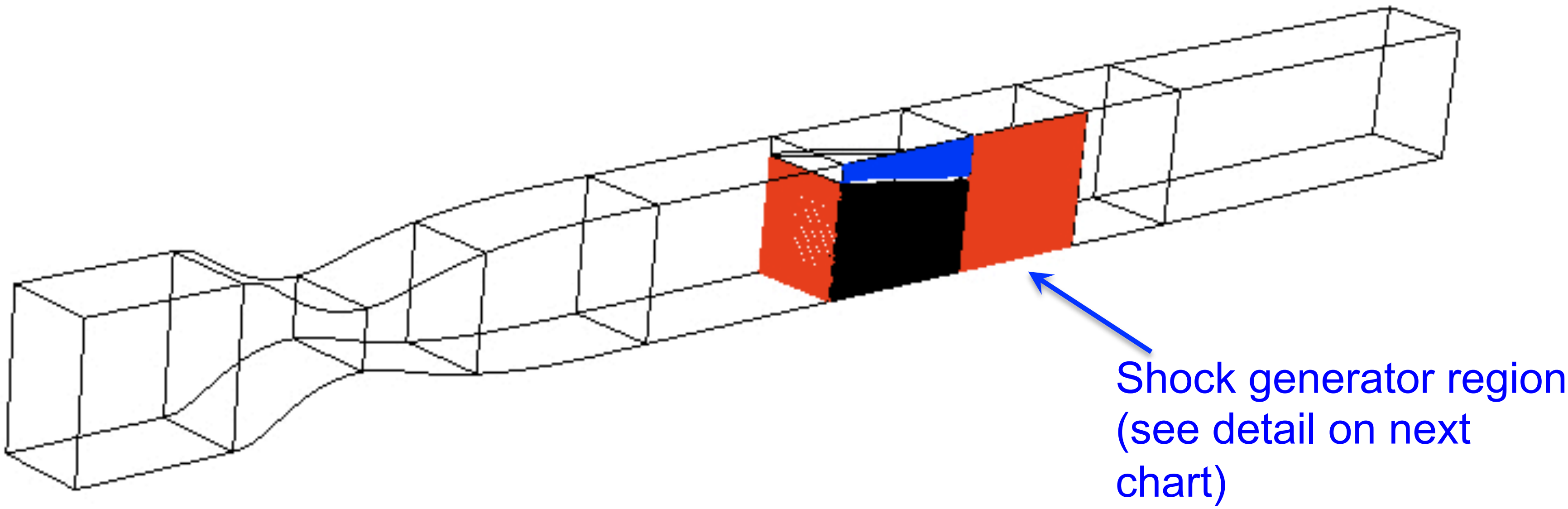
U Velocities Along Symmetry Plane (12 degree wedge)

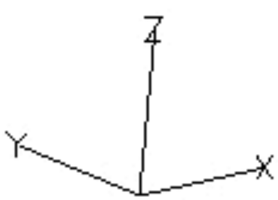


UFAST 8° Shock Generator, Mach 2.25

- Grid and solution details with SST turbulence model
- Comparisons of CFD solutions with experiment using SST, SA, ASM turbulence models

UFAST Grid (1 of 2)

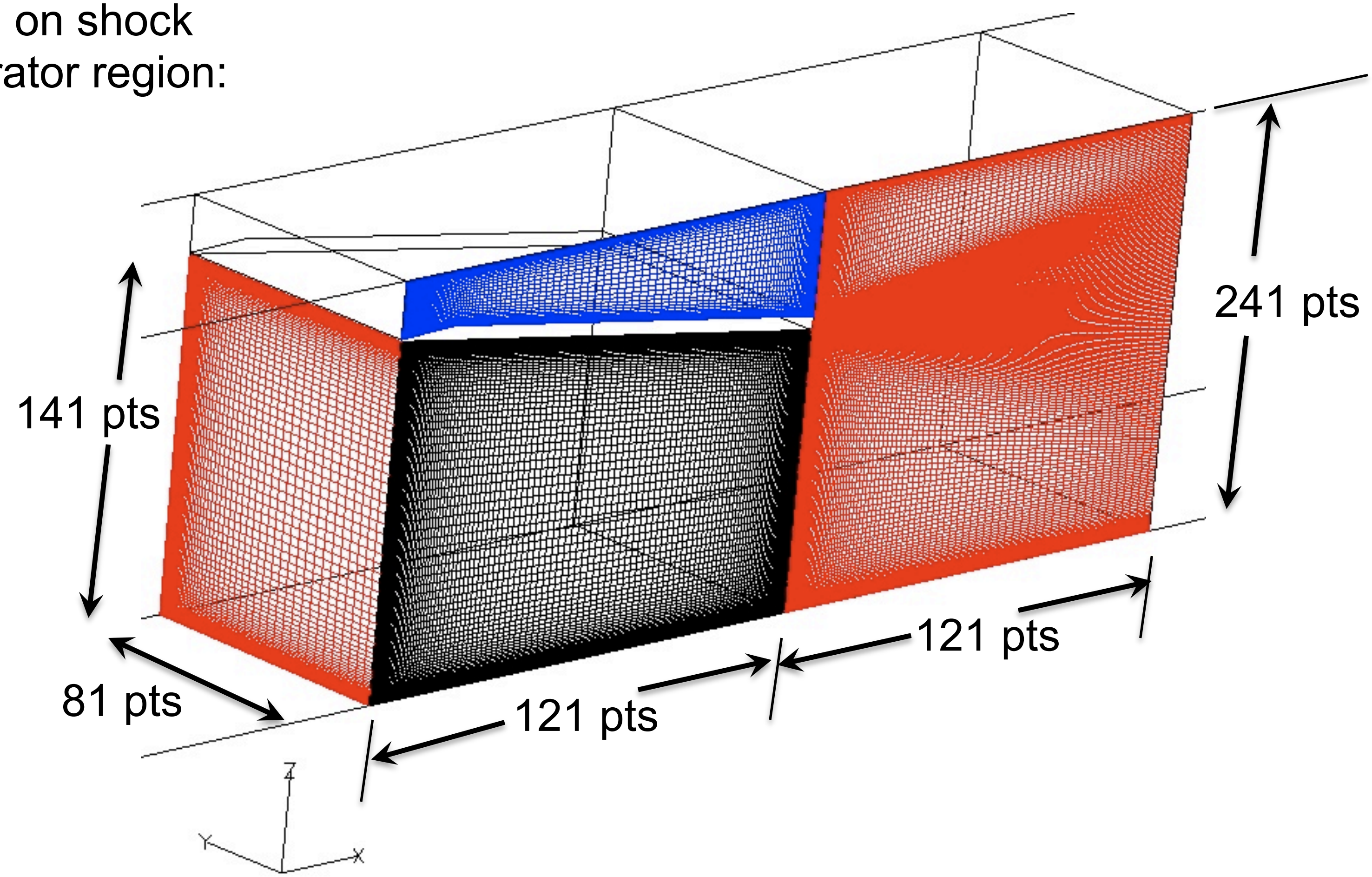




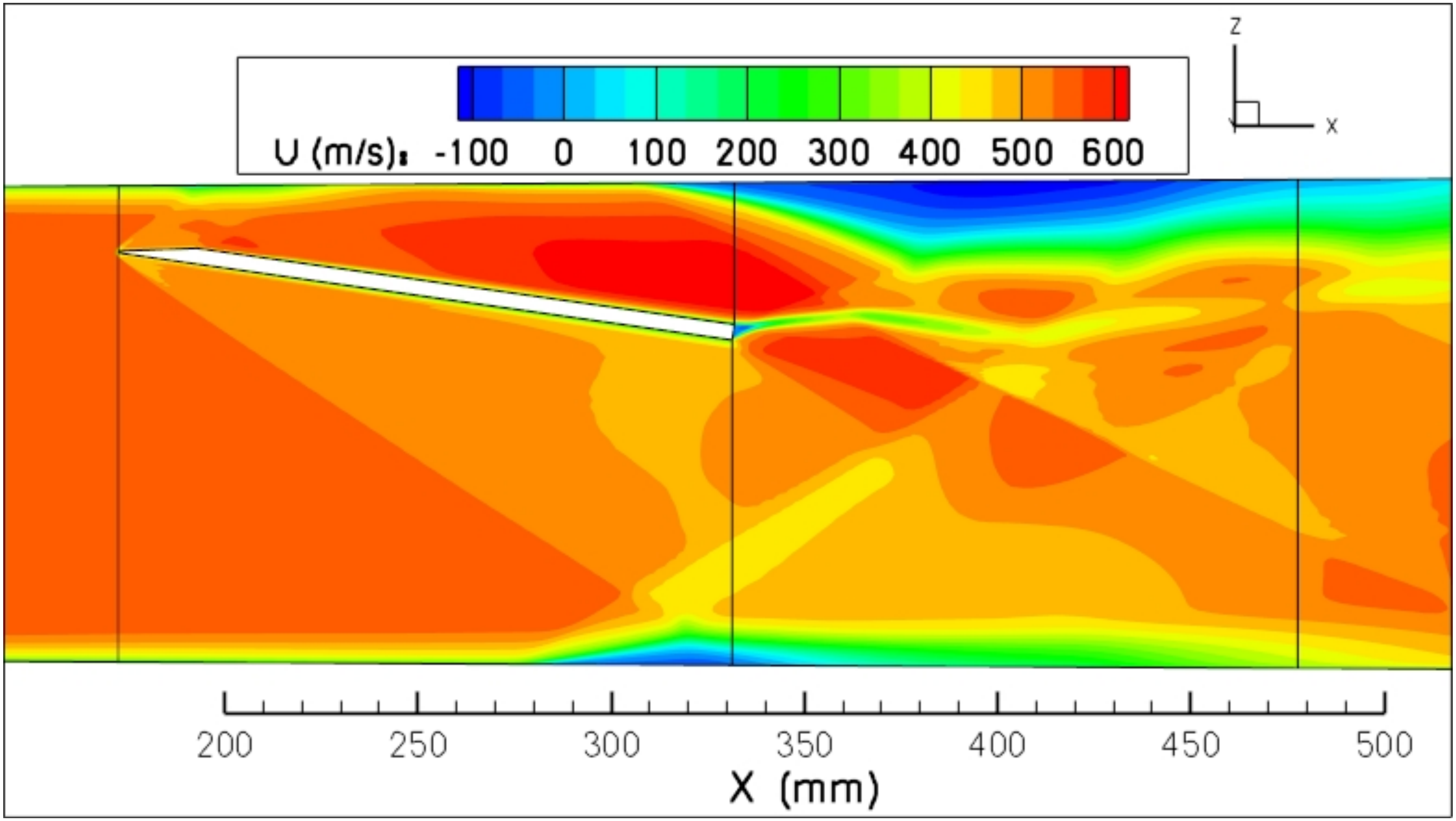
- 7.3 M grid points, 10 structured zones
- point-to-point connectivity in shock generator region
- y+ = 1.0 for no-slip walls (calculated using freestream conditions and "average" C_f =0.0025)
- $\Delta x+ \sim 60$ at key axial stations (i.e. changes in geometry)
- Grids smooth (no abrupt changes in packing) in shock generator region, within & across zones

UFAST Grid (2 of 2)

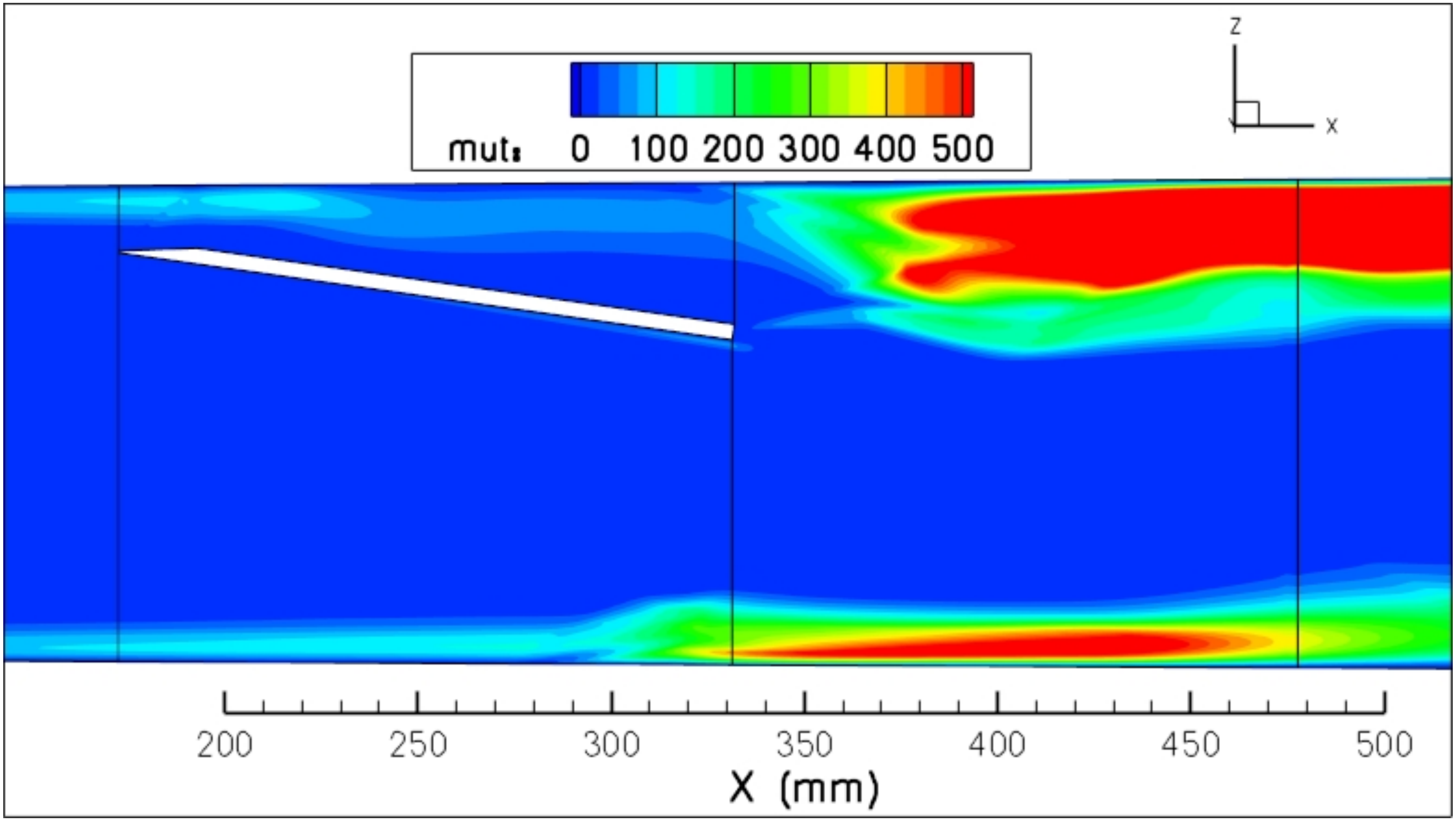
Zoom on shock generator region:



U Velocities Along Symmetry Plane



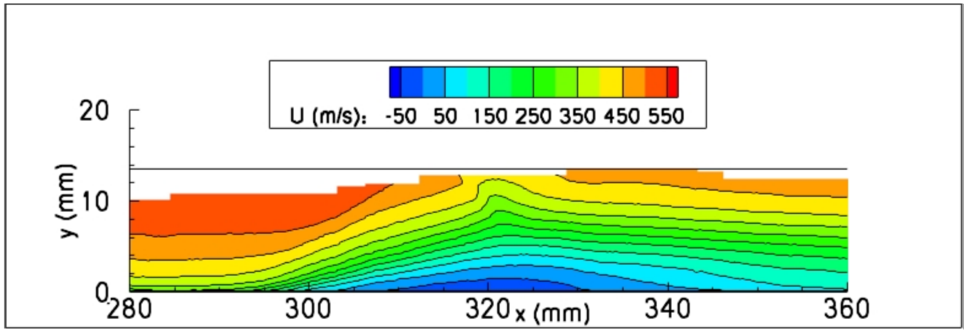
Eddy Viscosity Along Symmetry Plane



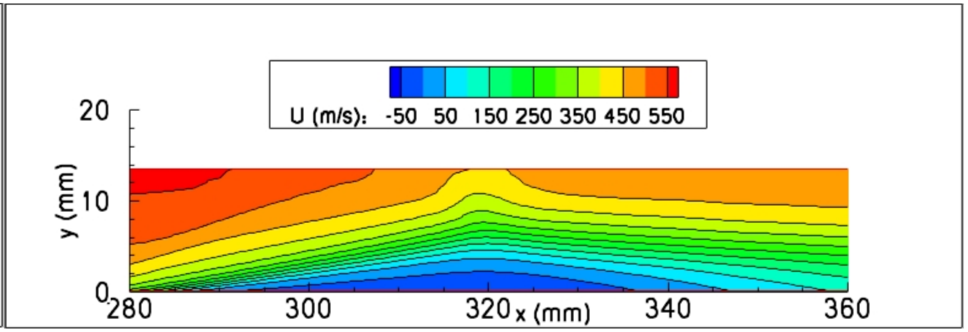
* *Contours shown are μ_t/μ_{ref} and are clipped on high end.*

U Velocity Contours

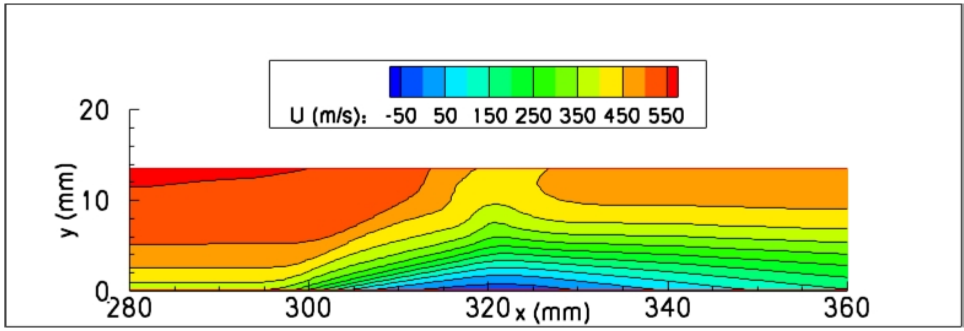
Experiment:



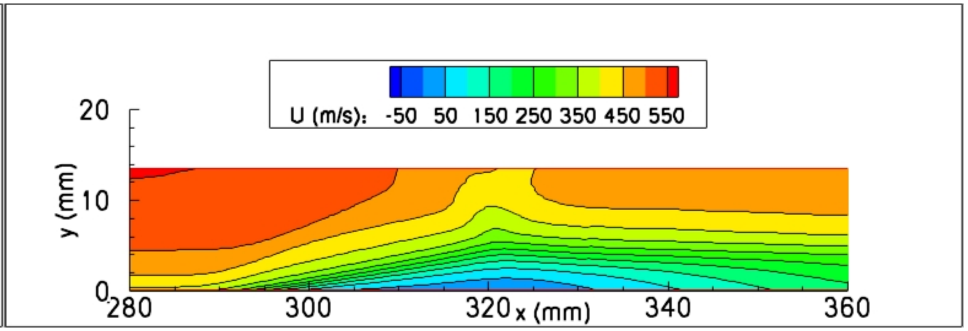
SST:



SA:

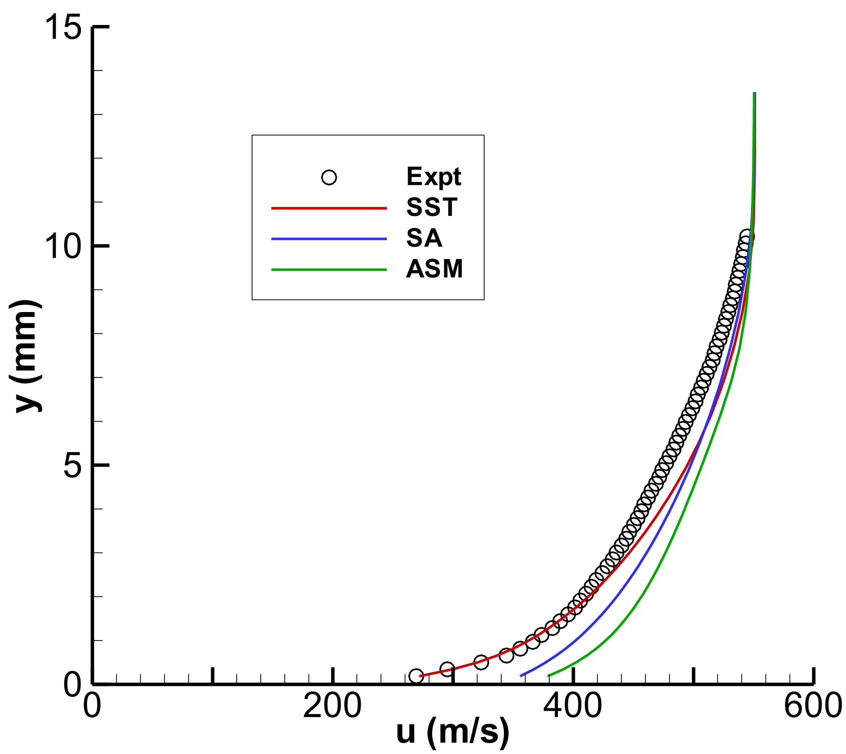


ASM:

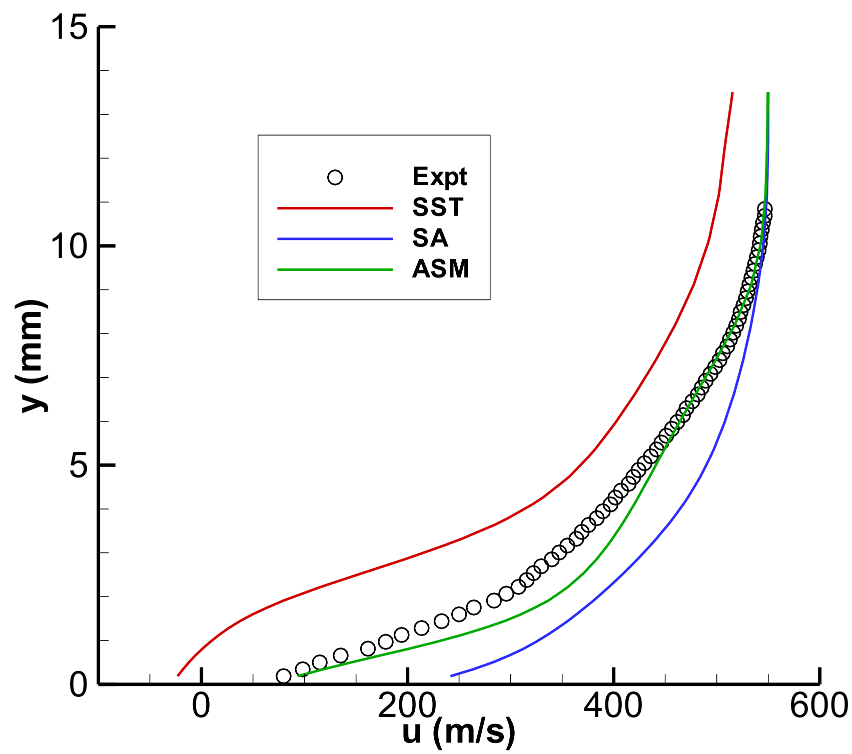


U Velocity Profiles

x = 280 mm

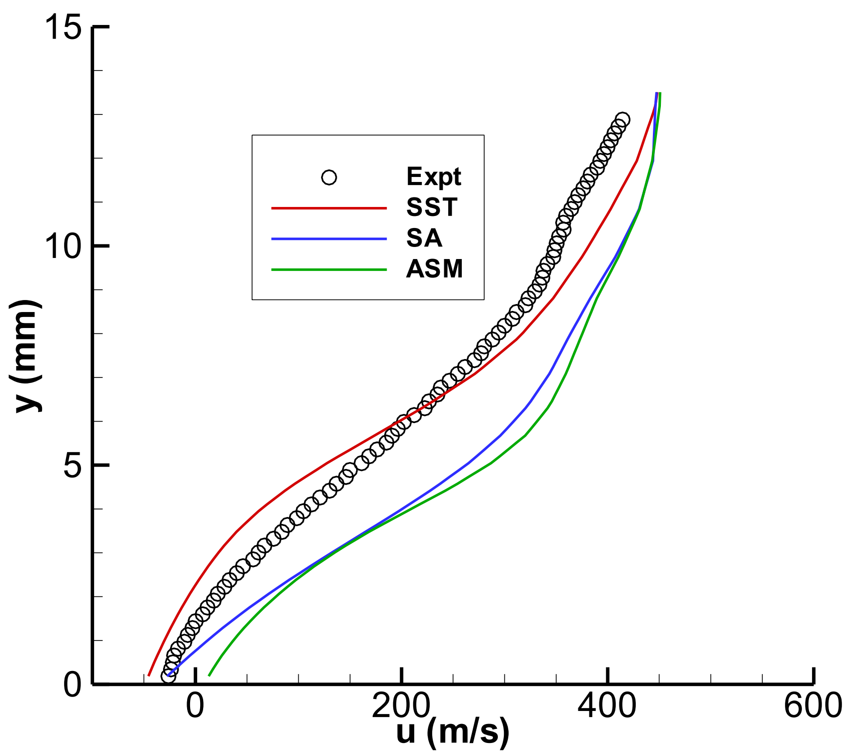


x = 300 mm

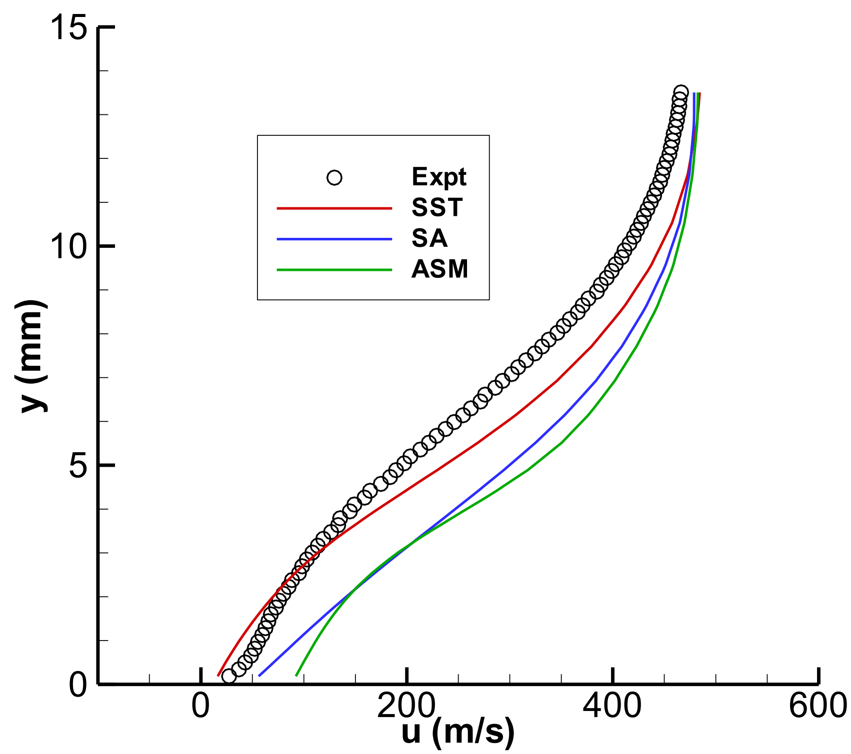


U Velocity Profiles

x = 320 mm



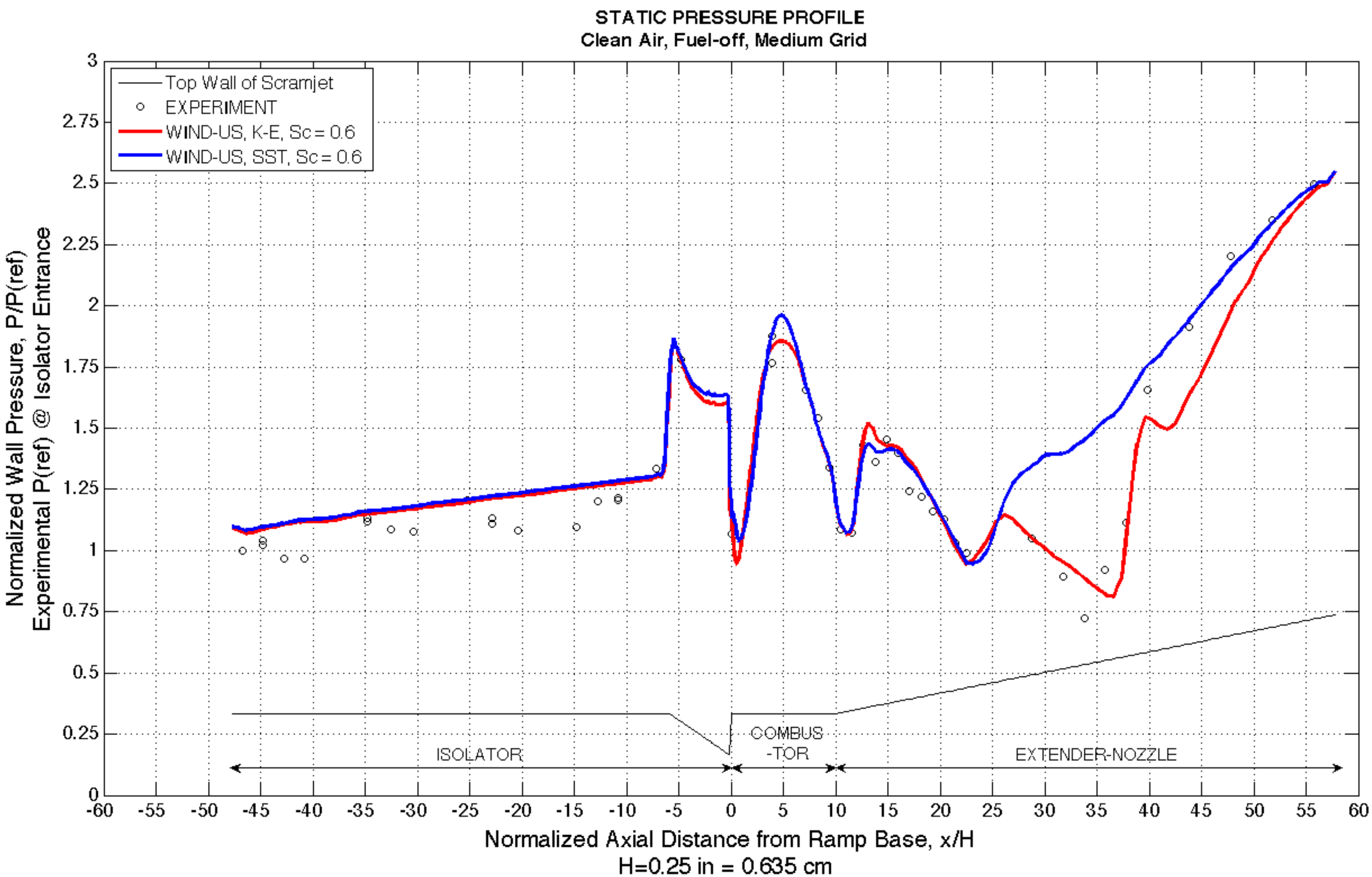
x = 340 mm



Summary of Cases Completed with Wind-US

- Solutions obtained with SST and SA for all 4 cases (3 U. Michigan cases & UFAST Case) on medium and fine grid levels.
- ASM solutions obtained for Michigan case 1 (7.75^o) & UFAST case, medium and fine grid levels.
- Numerical scheme investigations for U. Michigan case 1.

UVA – Direct Connect Scramjet



Conclusions

- Turbulence model effects are dominant, as expected.
- SST performs "best" however not great agreement. Further, our other experiences show SST failing for cases with more severe shocks & separations (i.e. isolators, overexpanded nozzles).
- Minimal effects of numerical scheme.
- Grid density investigations examined sequenced grids.
- Grid density investigations only examined sequenced grid. A more comprehensive study would target specific grid clustering to determine shock resolution needs. Current fine grid seems adequate, but finer grid needed to identify grid convergence.